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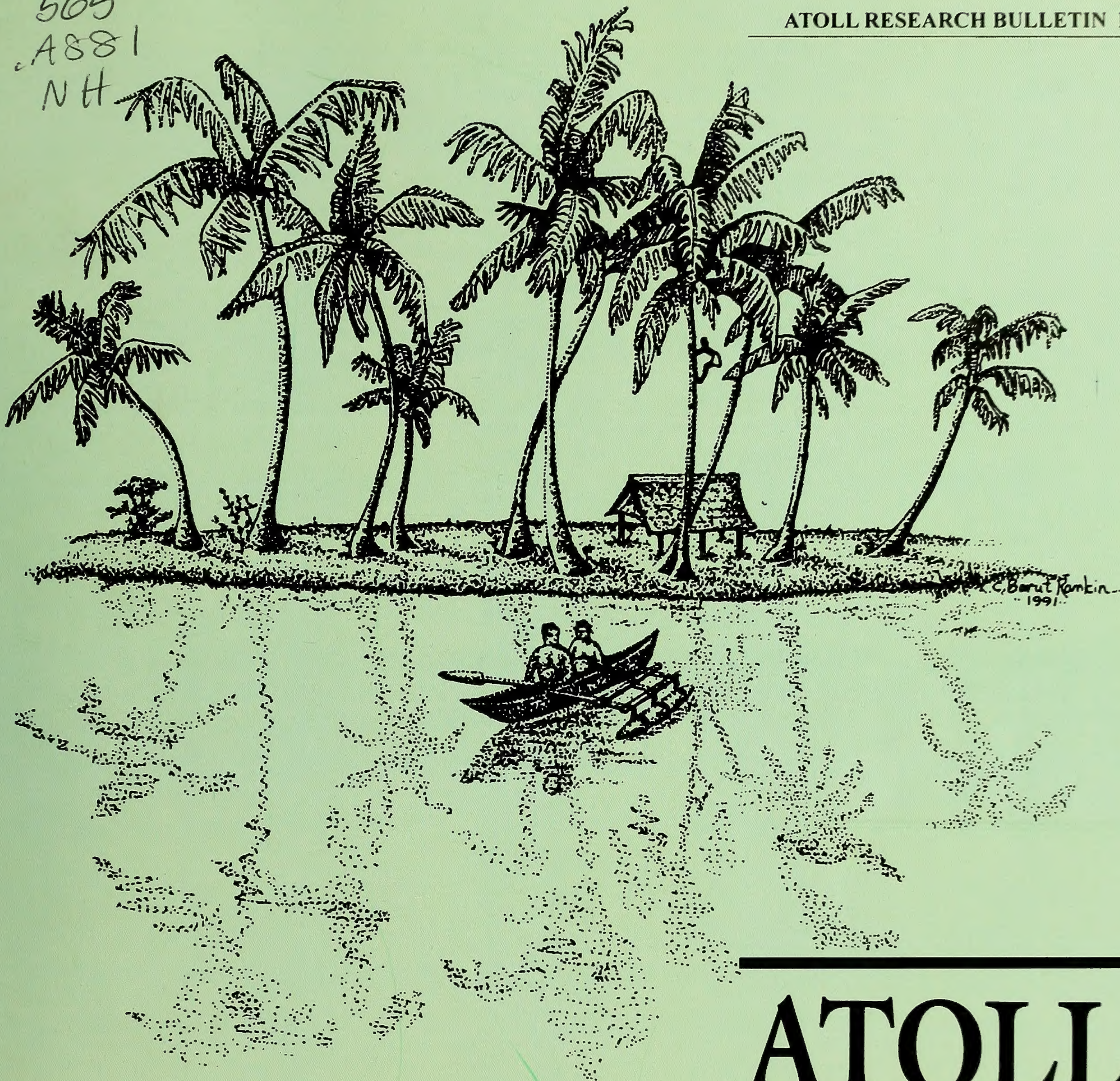

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TSUNAMIS AND CORAL REEFS

Edited by
David R. Stoddart

Issued by

NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C. U.S.A.
JULY 2007

Khaled bin Sultan
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Foundation

This special edition of the tsunami impacts on coral reefs was made possible by the generous contribution of Khaled bin Sultan Living Oceans Foundation which is dedicated to the conservation and restoration of our living oceans (www.livingoceansfoundation.org).

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ACKNOWLEDGMENT

The Atoll Research Bulletin is issued by the Smithsonian Institution to provide an outlet for information on the biota of tropical islands and reefs and on the environment that supports the biota. This issue is partly financed and distributed with funds from Atoll Research Bulletin readers and authors.

The Bulletin was founded in 1951 and the first 117 numbers were issued by the Pacific Science Board, National Academy of Sciences, with financial support from the Office of Naval Research. Its pages were devoted largely to reports resulting from the Pacific Science Board's Coral Atoll Program.

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ACRONYMS

BAPPENAS	Baddan Perencanaan Pembangundn (National Development Planning Agency, Republic of Indonesia)
COADS	Comprehensive Ocean-Atmosphere Data Set
CORDIO	Coral Reef Degradation in the Indian Ocean (programme of the Swedish International Development Cooperation Agency – SIDA)
CRISP	Computer Retrieval of Information on Scientific Projects
DEWA	Division of Early Warning and Assessment (UNEP)
EPA	Queensland Environmental Protection Agency (Queensland Government)
EERI	Earthquake Engineering Research Institute
GHCN	Global Historical Climatology Network
IUCN	World Conservation Union (formerly International Union for the Conservation of Nature and Natural Resources)
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center (USA)
NGDC	National Geophysical Data Center (division of NOAA)
NOC	National Oceanography Centre, UK
NIWA	National Institute of Water and Atmospheric Research (New Zealand)
NOAA	National Oceanic and Atmospheric Administration (US Department of Commerce)
UNESCO	United Nations Educational, Scientific and Cultural Organization
WIIP	Wetlands International Indonesia Programme (of Wetlands International and the Indonesian Ministry of Forestry)
WWF	Worldwide Fund for Nature (formerly World Wildlife Fund)

CORAL REEFS AND THE TSUNAMI OF 26 DECEMBER 2004: GENERATING PROCESSES AND OCEAN-WIDE PATTERNS OF IMPACT

BY

THOMAS SPENCER

INTRODUCTION

The Indian Ocean tsunami of December 26, 2004 was the most catastrophic such event in recent history, killing more than 230,000 people in the near field and a further 70,000 in the Indian Ocean far field. This death toll was far in excess of the estimated 36,500 deaths associated with the tsunami waves generated by the cataclysmic explosion of Krakatau on August 26-27, 1883 (Abercromby et al., 1888; Winchester, 2003). It was also quite clearly the best-documented tsunami of all time, both scientifically and in terms of the very real human tragedies delivered in almost real-time by the global communications revolution. Scientific data gathered to understand this event, and thus to better predict future such catastrophes, have included not only the application of now well-established techniques at the local-to-regional spatial scale such as the remote sensing of coastal margins (CRISP, 2005) and ocean-surface heights (NOAA, 2005a), multibeam swath bathymetry of the earthquake zone (Wilson, 2005) and handheld GPS-controlled surveys both above and below water but also the products of newly emerging technologies at the global scale such as the spectacular seismic monitoring delivered by the Global Seismographic Network (Park et al., 2005a) of digital broadband, high dynamic range seismometers, the pattern of large-scale displacements revealed by the network of 41 continuously recording GPS stations throughout Southeast Asia (Bannerjee et al., 2005) and the detection of earthquake and tsunami-induced deep infrasound in the central Indian Ocean (Garces et al., 2005).

It has also been the best mathematically modelled, simulated and visualized tsunami in history. At the same time, it has not always been easy to establish common points of reference between the many nation states impacted by the disaster, to set detailed local studies within wider regional pictures and to separate out anecdotal reports from scientific facts. This paper attempts to place the December 2004 tsunami in its contemporary, historical and possible near-future tectonic contexts. It also attempts to provide a regional synthesis which highlights the regional variability in tsunami wave characteristics. It is hoped that individual site reports on tsunami impacts of coral reefs and associated shallow marine ecosystems can be placed within this framework and thus better understood.

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WHY, WHERE AND WHY NOW: THE PLATE TECTONIC FRAMEWORK

Southeast Asia is characterized by the convergence of the oceanic Indo-Australian plate, at an average rate of 7.0 cm a^{-1} in the direction 003 deg, with the extension of the continental Eurasian plate comprising the Malay Peninsula, Sumatra, the Sunda Shelf sea and parts of Borneo (Simandjuntak and Barber, 1996). Where the two plates meet, the oceanic plate is subducted beneath the continental plate. This tectonic setting is expressed in a nearly continuous arc of volcanic and non-volcanic islands and associated deep-water trench and back-arc basins, which extends from Myanmar and the collision zone with India and the Himalayas to Timor and the collision zone of Sumatra's outer-arc ridge with Papua and Australia (Fig. 1; Hutchinson, 2005). The character of convergence changes from east-to-west. In the east, south of Java, relatively old (ca. 100 Ma) oceanic lithosphere is subducted in a direction perpendicular to the trench orientation. However, to the northwest, the relatively young (ca. 40 Ma) oceanic lithosphere behaves rather differently. Not only does the convergence rate reduce (from 7.8 cm a^{-1} at Sumbawa to 6.0 cm a^{-1} in the Andaman Islands) but the convergence also becomes increasingly oblique (Fitch, 1972). Thus convergence needs to be partitioned into two components comprising both trench-normal subduction and forces parallel to the trench which generate strike-slip motions along major fault systems (Fig. 2; McCaffrey, 1996). As a result of these dynamics, a sliver plate, the Burma plate, has sheared off parallel to the subduction zone and sits between the convergent plate margin to the west and great fault systems to the east which comprise (from south-to-north) the Sumatra Fault, the West Andaman Fault (the spreading ridge of the Andaman Sea basin) and the Sagaing Fault in Myanmar (Figs. 1 and 2; Malod and Mustafa Kemal, 1996; Curray, 2005). It was this microplate, and its relations with the Indo-Australian plate, that was involved in the December 2004 tsunami.

In interseismic periods, strain accumulates on the locked fault between the oceanic and continental plates. These stresses are then periodically released in large "megathrust" earthquakes associated with the rupture of this boundary. These earthquakes may in turn generate tsunamis. Tsunami databases variously list 64 tsunami events in the Indian Ocean between 1750 and 2004 (NGDC, 2005) and 87 events between 1640 and 2005 (Siberian Division, Russian Academy of Sciences, 2005). Table 1 lists those earthquakes "definitely" or "probably" (NGDC (2005) terminology, categories 4 and 3) generating tsunamis since 1797 for the section of the Sunda Arc from SW Sumatra (5°S) to the northern Andaman Islands (13°N). Figure 3 shows the location of large historical earthquakes between 2 and 14°N, historical seismicity 1964-2004 and aftershocks to January 14 following December 26. It is known, for example, that the 1797, 1833 and 1861 earthquakes (Fig. 4) all produced tsunamis both on the islands and the Sumatran coast, as well as resulting in significant vertical adjustments (Newcomb and McCann, 1987). Thus the 1833 earthquake appears as a large emergence event in the fossil coral microatolls on the reefs of Sumatra's outer-arc ridge. Stratigraphic analysis of both fossil and living microatolls has allowed Zachariasen et al. (1999) to identify emergence of 1

to 2 m increasing towards the trench. They argue that this pattern and magnitude of uplift is consistent with about 13 m of slip on the subduction interface and suggest an upwards revision of the magnitude of the earthquake to 8.8-9.2. The December 2004 earthquake and resulting tsunami were, therefore, not unusual historically in terms of location, general characteristics and type of impacts. Where it differed, however, was in the magnitude of those effects, its spatial scale and the complex nature of its energy release.

Figure 1. Tectonic setting of Southeast Asia (after Hutchison, 2005).

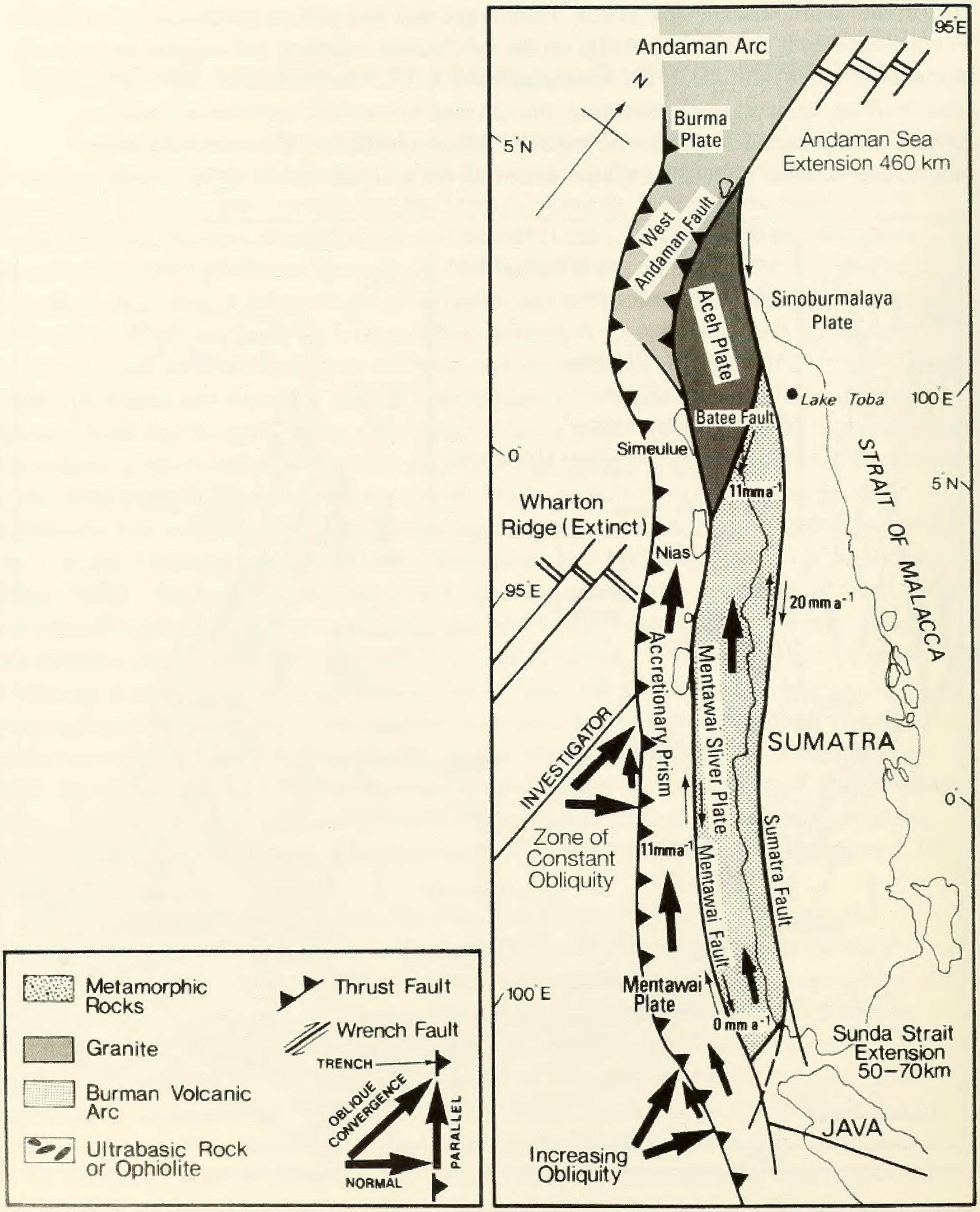

Figure 2. Fault structures of Sumatra (after Malod and Mustafa Kemal, 1996 and Hutchinson, 2005).

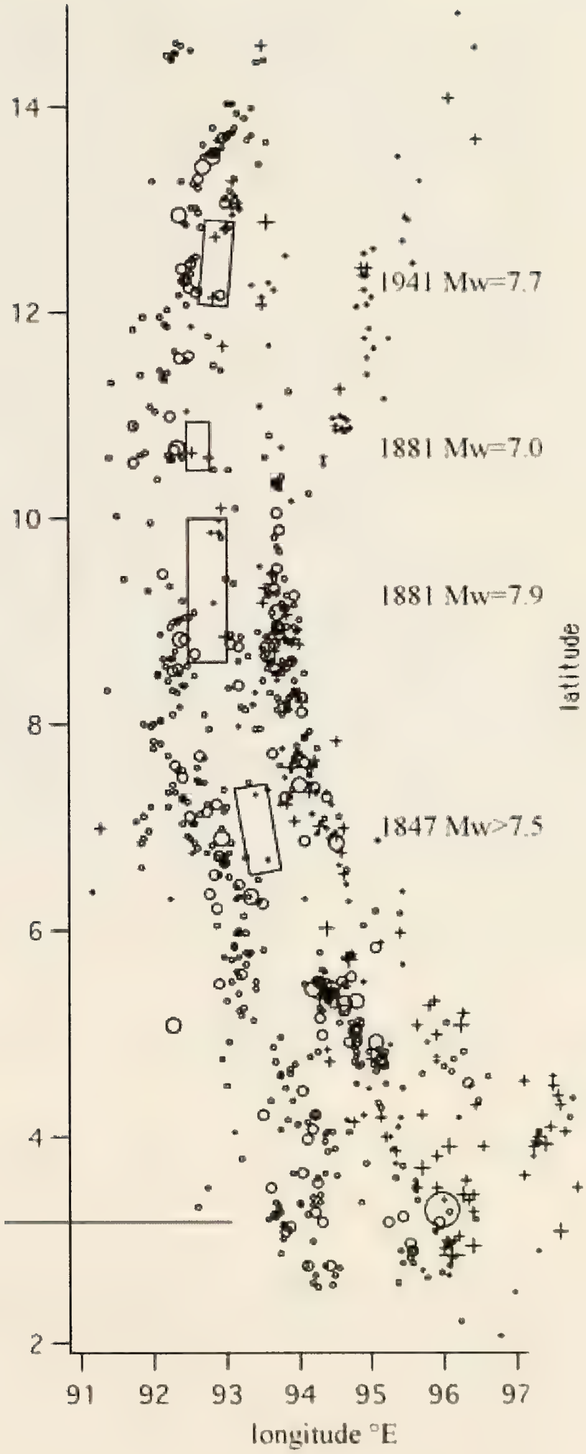

Figure 3. Large historical earthquakes between 2 and 14oN. Open circles are aftershocks to 14 January 2005 following the 26 December 2004 earthquake and crosses are seismic events (mostly > M = 5.5) 1964-2004) (after Bilham et al., 2005).

Table 1. Earthquakes 'definitely' or 'probably' generating Indian Ocean tsunamis along the Sunda Arc between 5°S and 13°N, 1797-2005.

Date	Mag.	Location	Latitude	Longitude	Depth of Earthquake (km)	Slip along megathrust (m)	Tsunami run-up (m)	Source/s
10/2/1797	8	W Sumatra	- 1.00	99.00		a few metres		NGDC 2005, Nalbent *et al.* 2005
24/11/1833	8.2	SW Sumatra	- 3.50	102.20		10 to 13		NGDC 2005, Zachariasen *et al.*
	1999,							Nalbent *et al.* 2005
5/1/1843	7.2	W Sumatra	1.50	98.00				NGDC 2005
31/10/1847	7.9	Little Nicobar	7.33	93.67				NGDC 2005, Bilham *et al.* 2005
16/2/1861	8.5	W Sumatra	- 1.00	97.50				NGDC 2005
9/3/1861	7	W Sumatra	0.30	99.37				NGDC 2005
26/4/1861	7	W Sumatra	1.00	97.50				NGDC 2005, Nalbent *et al.* 2005
25/9/1861	6.5	W Sumatra	- 1.50	100.00				NGDC 2005, Nalbent *et al.* 2005
19/8/1868		Andamans	11.67	92.73			4	NGDC 2005, Nalbent *et al.* 2005
31/12/1881	7.9	Car Nicobar	9.00	92.00	15	2.70	1.2	NGDC 2005, Bilham *et al.* 2005
4/1/1907	7.6	W Sumatra	2.00	94.50			2.8	NGDC 2005
6/2/1908	7.5	SW Sumatra	- 5.00	100.00			1.4	NGDC 2005
25/9/1931	7.5	SW Sumatra	- 5.00	102.70			31.4	NGDC 2005
28/12/1935	7.9	W Sumatra	0.00	98.25		2.3		NGDC 2005, Nalbent *et al.* 2005
26/6/1941	8.1	Andamans	12.50	92.50	50	<3		NGDC 2005, Bilham *et al.* 2005
2/4/1964	7	NW Sumatra	5.90	95.70			0.7	NGDC 2005
24/2/1982	5.4	NW Sumatra	4.37	97.70				NGDC 2005
13/9/2002	6.7	Andamans	13.04	93.07	33			NGDC 2005
26/12/2004	9.3	NW Sumatra	3.32	95.86	20 to 30	11 to 23	34.9	NGDC 2005, Bilham *et al.* 2005 McCloskey *et al.* 2005, Stein and Okal 2005b
28/5/2005	8.7	NW Sumatra	2.07	97.01	30			USGS 2005

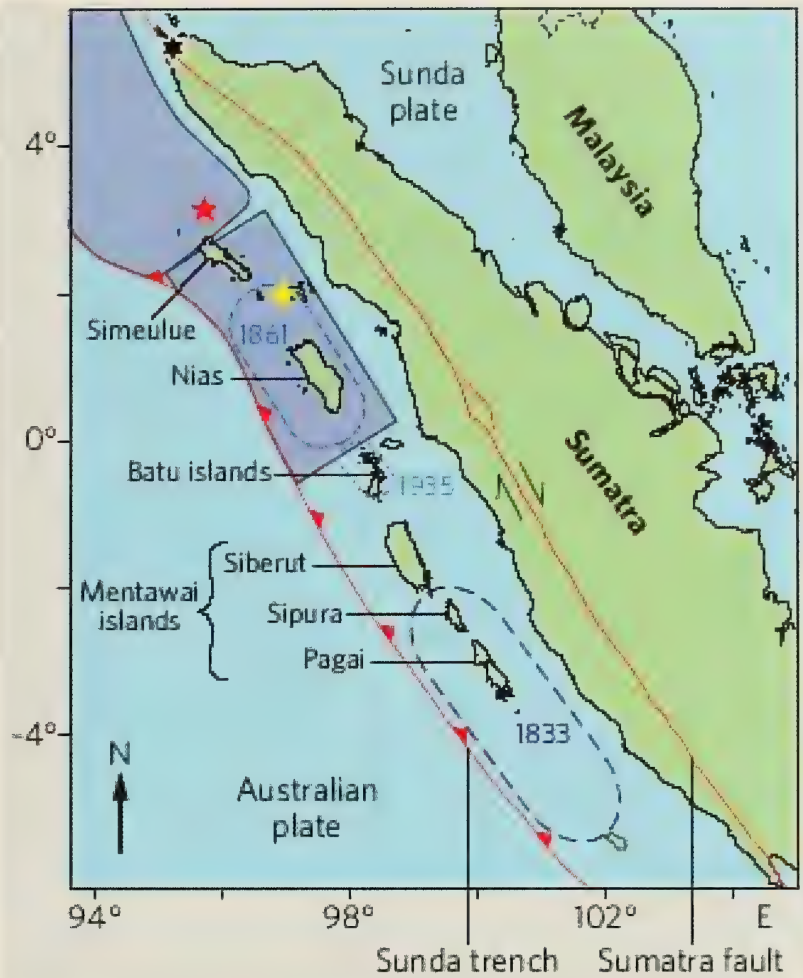

Figure 4. Large historical earthquakes between 4°N and 4°S on the Sunda Arc. Dotted lines indicate approximate extents (the 1797 event is not shown but most probably overlaps significantly with the 1833 event). Stars mark locations of epicenter of December 2004 (red) and March 2005 (yellow) events (after Nalbant et al., 2005).

WHAT HAPPENED: GENERAL CHARACTERISTICS OF THE EARTHQUAKE OF DECEMBER 26, 2004

The 2004 Sumatra–Andaman earthquake was the largest event since the Good Friday Alaskan earthquake of March 27, 1964, and the second largest since modern seismographic recording began a hundred years ago, releasing as much strain energy as all the global earthquakes between 1976 and 1990 combined (Park et al., 2005a). The earthquake's epicenter located at 3.3°N, near the northern end of the island of Sumatra. The rupture began at 00:58:47 Coordinated Universal Time (UTC) on December 26, 2004 affecting a 100 km section of the plate boundary. After one minute, and for the next four minutes, the "unzipping" of the plate boundary accelerated to a rate of 3 km s^{-1} to the

north–northwest before slowing to an extension rate of 2.5 km s^{-1} for a further six minutes (Ammon et al., 2005; de Groot-Hedlin, 2005; Ni et al., 2005; Singh, 2005). It passed close to, or through, the rupture zones of the major historic earthquakes of 1847, 1881 and 1941 with apparent indifference (Bilham et al., 2005). Ground movements began in Sri Lanka four minutes after the onset of rupture, the peak-to-peak ground shaking for surface Rayleigh waves at the Global Seismographic Network station at Pallekele, Sri Lanka (station code: PALK) being 9.2 cm (Park et al., 2005a). Particularly remarkable was the slow movement of the northern limit of the rupture, where it took over 30 minutes for the final slippage to be completed in the Andaman Islands. It was this energy release that accounted for one-third of the total energy in the earthquake, resulting in it being upgraded from a moment magnitude of 9.0 to 9.3 and making the earthquake some two and a half-to-three times larger than first reported (Fig. 5; Park et al., 2005b; Stein

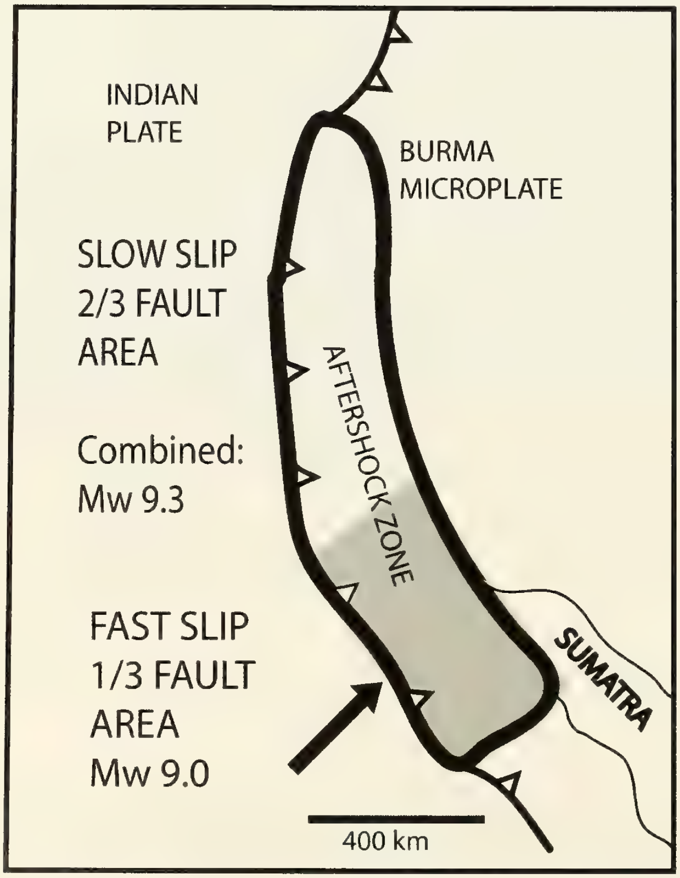

Figure 5. Areas of "fast slip" and "slow slip" associated with the December 26, 2004 earthquake (after Stein and Okal, 2005b).

and Okal, 2005a, 2005b). Similarly, the total rupture length was 1300 km, trebling the area initially thought to be affected (Stein and Okal, 2005c).

The megathrust occurred at a depth of 20–30 km with the Burma plate rebounding upwards by 10 m at the epicenter. This displaced 30 km^3 of seawater and, by reducing the volume capacity of the Bay of Bengal and the Andaman Sea through sea floor uplift,

raised global sea level by 0.1 mm (Bilham, 2005). Displacement occurred across a shallow-dipping surface, the western side being uplifted and the eastern side depressed. Gravity changes, seen in remotely sensed geoid anomaly patterns, suggest a 60 km–wide zone of uplift of ca. 2.5 m over a distance of 1000 km, flanked to the northeast by a narrower zone of subsidence of ca. 3 m (Sabadini et al., 2005). Uplift of ca. 1.5 m characterized the SW coast of Simeulue Island, totally exposing the former fringing reef (Sieh, 2005). The area of subsidence intersected the coastline of northern Sumatra. Comparison of elevation data pre- and post-tsunami in the city of Banda Aceh indicate subsidence of 0.28–0.57 m, with other coastal locations showing sinking of 1–2 m (USGS, 2005a).

There is evidence throughout the Nicobar and Andaman islands of considerable changes in land level following the earthquake. At the southernmost tip of Great Nicobar, the benchmark provided by the foundations of the Indira Point lighthouse indicates subsidence of 4.25 m (although see also Ramanamurthy et al., 2005 for lower estimates of subsidence on Great Nicobar), with 4 to 7 m of subsidence at Katchall and extensive flooding on neighboring islands (Bilham et al., 2005). At Car Nicobar, the eastern coast subsided by 1–2 m with uplift of up to 1 m on the western shore. This tilting mirrors that experienced in the New Year's Eve earthquake of December 31, 1881 (Oldham, 1884) but of an order of magnitude greater (Ortiz and Bilham, 2003). Little Andaman, Rutland and North Sentinel, Andaman Islands all appear to have been uplifted by 1 to 2 m with the pre-earthquake lagoon at North Sentinel now completely exposed (Bilham et al., 2005). By comparison, Port Blair suffered subsidence, although the exact magnitude is unclear, with reports giving figures of between 0.25 and 2.0 m (Bilham et al., 2005; Ramanamurthy et al., 2005). Finally, the western coast of Middle Andaman and Diglipur, North Andaman were uplifted by 1 to 2 m and 0.5 to 0.8 m respectively (Bilham et al., 2005). Taken together, these data suggest plate boundary slip estimated at 15–23 m in the Nicobar Islands and 5–10 m in the Andamans (Bilham et al., 2005). These estimates are consistent with a predicted 12–15 m of slip based on maximal tsunami run-up statistics, model solutions based on seismic datasets which are best fitted by 11 m of slip (Stein and Okal, 2005b) and 11–14 m of displacement calculated from continuous GPS observations in the region (Ammon et al., 2005; Kahn and Gudmundsson, 2005). In addition, it appears that the earthquake was accompanied by horizontal displacements in the Nicobar and Andaman Islands of 1–4 m (Bilham et al., 2005). Similarly, it has been estimated that the coastline of Sumatra moved by up to 3 m horizontally and the northern end of Simeulue Island by 2 m (NASA, 2005).

CONTROL OF TSUNAMI CHARACTERISTICS BY THE SUMATRA-ANDAMAN EARTHQUAKE

It is sobering to realize that earthquake generation of tsunamis is a highly inefficient process; Lay et al. (2005) have calculated that the energy of the December 2004 tsunami was equivalent to less than 0.5 % of the strain energy released by the faulting. Nevertheless, earthquake characteristics play an important role in determining the magnitude, timing and pathways of tsunamis. In particular, for the December 2004

event there has been discussion as to the relative importance of the energy released in the early and later stages of the earthquake to tsunami dynamics. Bilham (2005) has taken the view that slip occurred too slowly in the last five minutes of the earthquake to have contributed to tsunami generation whereas Stein and Okal (2005c, 2005d) have argued that the late stage "slow slip" helped excite the tsunami. What is clear is that simulation models based on only the southern segment of the rupture zone (e.g., NIO - National Institute of Oceanography, 2005) show maximum tsunami wave heights propagating in a southeasterly direction into the Indian Ocean with lower wave heights on its northern boundary past Sri Lanka, whereas simulations based on activity along the whole fault (e.g., Satake, 2005) show a strong east-west component with weaker amplitudes to the

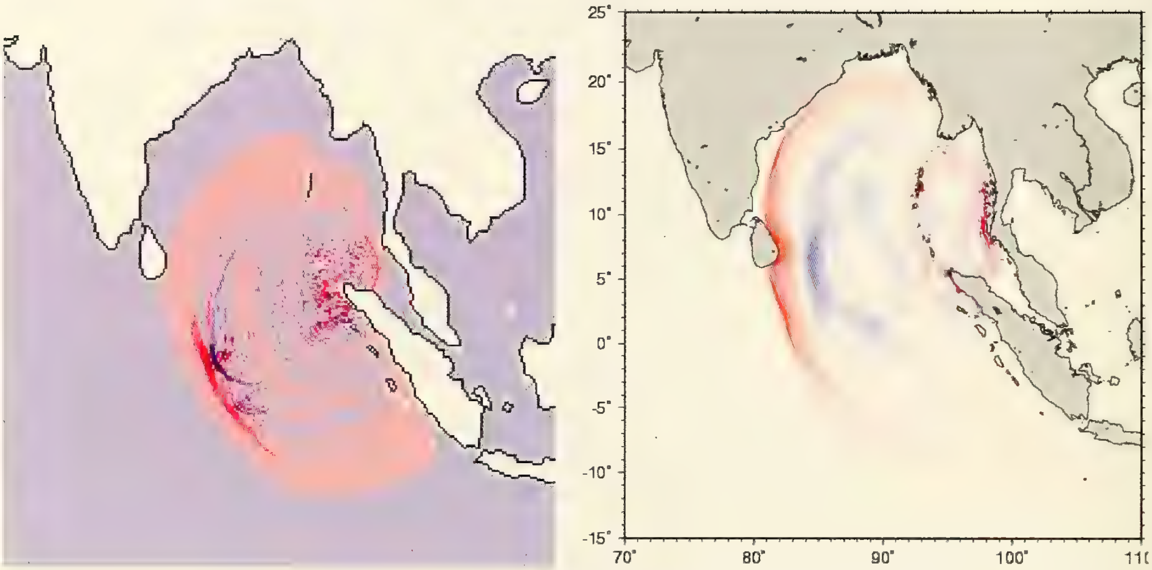

Figure 6. Simulation modelling of the tsunami wave front. Left: based on south segment of rupture only. Right: based on entire fault length, after 100 minutes. (after Stein and Okal, 2005b).

north, into the Bay of Bengal, south (e.g., Cocos Island) and southeast (e.g., eastern Java and Lombok) (Fig. 6).

The catastrophic impacts on the eastern coastline of Sri Lanka and the west coast of mainland SE Asia are clearly visible in these and other simulations (for example, *inter alia*: European Commission, 2005; NOAA, 2005b; Siberian Division of the Russian Academy of Sciences, 2005; USGS, 2005c). Something of a compromise is offered by Lay et al. (2005) who identify the source region for the initial wave front as extending from the epicenter for 600–800 km to the northwest, terminating in the Nicobar Islands. Tsunami amplitudes are greatest perpendicular to generating structures; thus the strong north-south orientation of the faultline over this distance led to the greatest wave energy being in an east-west direction (Fig. 7; Lomnitz and Nilsen-Holseth, 2005). Furthermore, the extension of earthquake activity beyond the northern tip of Sumatra led to more extensive impacts on the coastline of Thailand and southern Myanmar than might have been expected had there been a sheltering effect from the large Sumatran landmass.

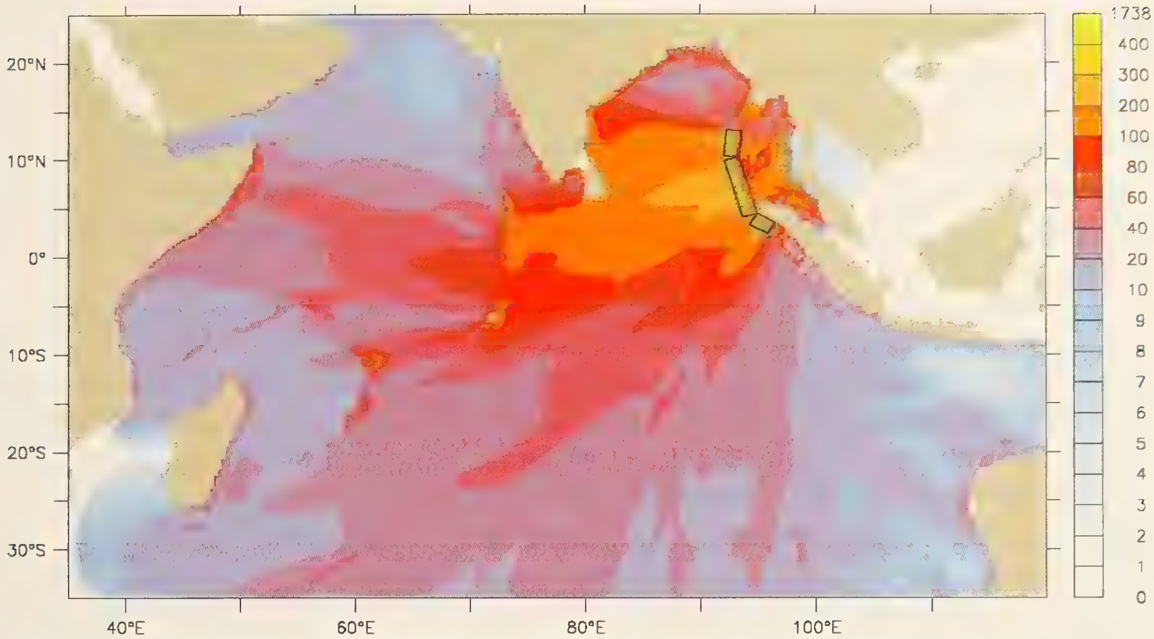

Figure 7. Maximum computed wave heights (cm) in the Indian Ocean (U.S. National Oceanic & Atmospheric Administration (NOAA) and U.S. National Tsunami Hazard Mitigation Program (available at http://www.pmel.noaa.gov/tsunami/indo20041226/max.pdf).

CHARACTERISTICS OF THE 26 DECEMBER 2004 TSUNAMI

Travel Times

The Jason 1 altimetry satellite passed over the front of the tsunami wave at 5°S about two hours after the earthquake. Plots of sea surface height changes between this and both preceding and succeeding satellite passes indicate a trough-to-crest tsunami wave height of 1m, a wavelength of 430 km, a wave period of 37 s and a wave velocity of 200 m s^{-1} (Gower, 2005). Travel times of the first arrival of the tsunami wave within and around the Indian Ocean basin varied from ca. 30 minutes at Simeulue Island (Yalciner et al., 2005a) and 38 minutes at Port Blair, Andaman Islands (Bilham et al., 2005) to over 14 hours at Cape Town, South Africa. Computed arrival times are shown in Figure 8 and measured arrival times from tide gauge records are reported in Table 2A and B. The northern regions of Sumatra were struck quickly, within one hour of the initial rupture. Tsunami waves reached Sri Lanka, the east coast of India and the Maldives archipelago in ca. 2-3 hours, giving typical propagation speeds of 187 m s^{-1} in deep water. Thailand was also struck some 2 hours after the earthquake, despite being closer to the epicenter, because the tsunami travelled more slowly over the shallow eastern margin of the Andaman Sea basin; here propagation speeds were ca. 160 m s^{-1}. These figures compare well with the estimates of the velocity of the Krakatau tsunami of 173 m s^{-1} (Abercromby et al., 1888). Tsunami waves reached the Seychelles and Mauritius in ca. 7 hours and the coast of East Africa in ca. 9 hours. NOAA (2005b) animations show ocean basin scale refraction of the tsunami wave front around southeastern Sri Lanka and southern India. Of the three major wave trains to affect Sri Lanka, the first two waves, 3 to 4 hours after the earthquake, were refracted around the southern tip of the island whilst the third wave,

after ca. 6 hours, appears to have been reflected from the coast of India (Fernando et al., 2005; Liu et al., 2005). Waves arriving on the NE coast of Penang Island in the Strait of Malacca were reflected from the mainland (Yalciner et al., 2005b). Modelling also shows smaller scale refraction effects in the Maldives, Chagos Archipelago and across the Mascarene Plateau between Seychelles and Mauritius. Wave refraction patterns across the shallow Seychelles Bank resulted in wave convergence in the lee of the island of Mahé (Jackson et al., 2005).

Tsunami waves travelled into both the Atlantic and Pacific Oceans. The tsunami passed around Australia's southern coastline and moved northwards, being recorded in the tide gauge at Kembla, New South Wales and at several stations along the Queensland coast (Queensland Government, 2005), and eastwards, reaching New Zealand 16.5–17 hours (NIWA, 2005) to 18 hours (Mulgor Consulting Limited, 2005) after the earthquake. The tsunami signal was detected in tide gauge records at Valparaiso, Chile and at Callao, Peru after 24 and 31 hours respectively (Fisheries and Oceans Canada, 2005). In the North Pacific Ocean, arrival times in the Hawaiian Islands were after ca. 30 hours with the highest wave heights varying between 0.085 and 0.3 m. First arrivals occurred after 32.5 hours at La Jolla, California, ca. 37 hours at Vancouver Island, British Colombia, 39 hours at Kodiak, Alaska and 41 hours in the North Kuril Islands (Rabinovich, 2005a; Fisheries and Oceans Canada, 2005). In the Atlantic Ocean, the tsunami was recorded at Arraial do Cabo, Rio de Janeiro, Brazil after 22 hours (Candella, 2005), at St. Helena after 25 hours and after 31.5 hours at Halifax, Nova Scotia, Canada where the amplitude was 0.43 cm and the wave period 45 minutes (Fisheries and Oceans Canada, 2005). At Newlyn, Cornwall, UK a small signal after ca. 31 hours was followed by a larger wave train of wave height 0.43 cm and wave period 45–60 minutes after 37.5 hours (Rabinovich, 2005b).

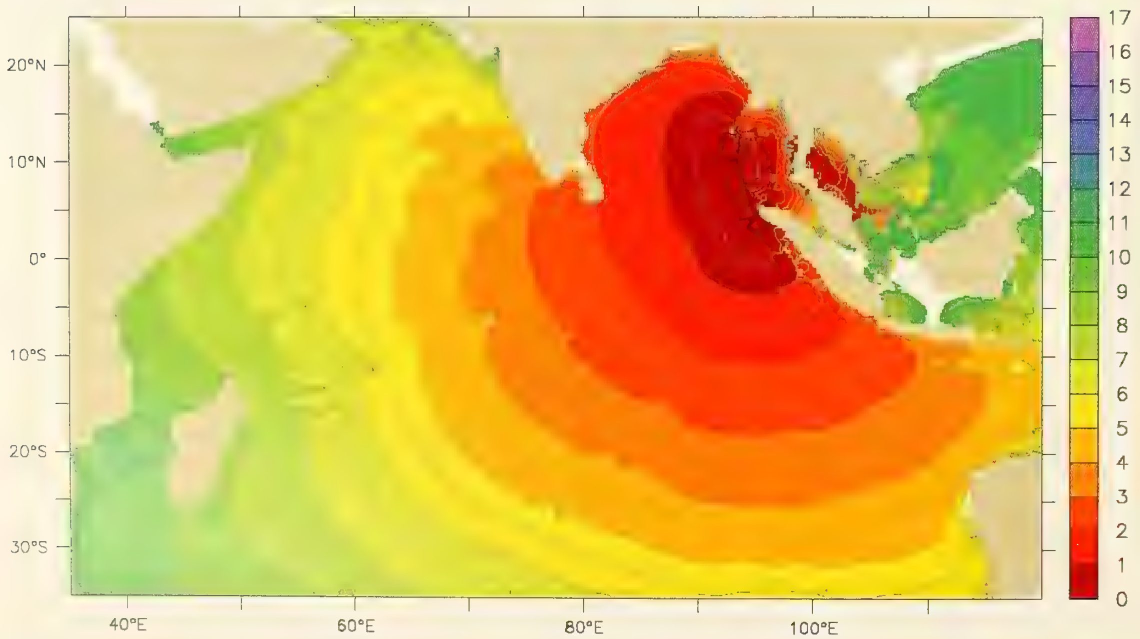

Figure 8. Computed arrival time of first wave (hours) in the Indian Ocean (U.S. National Oceanic & Atmospheric Administration (NOAA) and U.S. National Tsunami Hazard Mitigation Program (available at http://www.pmel.noaa.gov/tsunami/indo20041226/TT.pdf).

Table 2A. Tsunami of 26 December 2004: travel times (< 5 hours) and water level change.

Location		Travel Time	Height (m)	Source
Belawan	Indonesia	00.41	0.51	Merrifield *et al.* 2005
Sibolga	Indonesia	01.21	0.43	Merrifield *et al.* 2005
Lembar	Indonesia	01.51	0.15	Merrifield *et al.* 2005
Cocos	Australia	02.18	0.33	Merrifield *et al.* 2005
Prigi	Indonesia	02.21	0.15	Merrifield *et al.* 2005
Chennai	India	02.36	0.77	NIO (2005)
Visakhapatnam	India	02.36	1.51	NIO (2005)
Colombo	Sri Lanka	02.53	2.17	Merrifield *et al.* 2005
Panjang	Indonesia	03.00	0.11	Merrifield *et al.* 2005
Matara	Sri Lanka	03:10		Liu *et al.* 2005
Langkawi	Malaysia	03:15		Yalciner *et al.* 2005b
Male	Maldives	03.17	1.46	Merrifield *et al.* 2005
Gan	Maldives	03.21	0.88	Merrifield *et al.* 2005
Tuticorin	India	03.28	1.19	NIO (2005)
Hanimaadoo	Maldives	03.33	1.71 (1.80)	Merrifield *et al.* 2005 (AusAID 2005)
Penang	Malaysia	04:00		Yalciner *et al.* 2005b
Diego Garcia	BIOT	04.49	0.56	Merrifield *et al.* 2005

Travel times correspond to the difference between the onset of the earthquake and the time of arrival of the first wave (not necessarily the largest wave). Height is height of the first wave above mean tide.

Table 2B. Tsunami of 26 December 2004: travel times (> 5 hours) and water level change.

Location		Travel Time	Height (m)	Source
Kochi	India	05.41	0.81	NIO (2005)
Rodrigues	Mauritius	05.41		Merrifield *et al.* 2005
Mormugao	India	05.56	0.4	NIO (2005)
Port Louis	Mauritius	06:43 – 07:47		Merrifield *et al.* 2005
Hillarys	Australia	06.59	0.35	Merrifield *et al.* 2005
Saladah	Oman	07.13	0.28	Merrifield *et al.* 2005
Pt La Rue	Seychelles	07.17	1.09	Merrifield *et al.* 2005
Esperance	Australia	07.58	-0.01	Merrifield *et al.* 2005
Lamu	Kenya	08.57	0.28	Merrifield *et al.* 2005
Zanzibar	Tanzania	09.45	0.29	Merrifield *et al.* 2005
Portland	Australia	09.49	0.17	Merrifield *et al.* 2005
Richard's Bay	South Africa	11.04	0.16	Merrifield *et al.* 2005
Port Elizabeth	South Africa	12.22	0.26	Merrifield *et al.* 2005
Dumont D'Urville	Antarctica	13.34	0.06	Merrifield *et al.* 2005
Cape Town	South Africa	14.02	0.1	Fisheries and Oceans Canada Science (2005)

Travel times correspond to the difference between the onset of the earthquake and the time of arrival of the first wave (not necessarily the largest wave). Height is height of the first wave above mean tide. Rodrigues: last transmitted data as station destroyed by tsunami; Port Louis: time interval corresponding to period of data gap.

Wave Characteristics: Tide-Gauge Records

Satellite altimetry recorded typical open-ocean height increases of + 0.6 m two hours after the earthquake (NOAA, 2005a). Merrifield et al. (2005) have detailed tide gauge observations from 23 Indian Ocean stations, recording typical amplitudes of 0.1 to 0.5 m at relatively sheltered port and harbor locations in Indonesia (e.g., Fig. 9), Australia and East Africa (for selected stations see Fig. 10) but with peak water levels of 0.9–1.7 m in the Maldives (Fig. 11) and a maximum amplitude of 2.17 m at Colombo, Sri Lanka (Fig. 11).

To the east of the rupture, the tsunami signal was initially seen in the form of a wave trough. Thus at Sibolga, western Sumatra, a drop of 0.25 m (Merrifield et al., 2005) to 0.32 m (Kawata et al., 2005) was observed initially, then followed by a water-level rise of 0.82 m. This sequence was followed by a trend of falling sea level, totalling 1.79 m over the next two hours prior to a dramatic rise in water level of 2.72 m. A series of oscillations with an amplitude of over 1 m characterized the succeeding six-hour period (Fig. 9; Kawata et al., 2005).

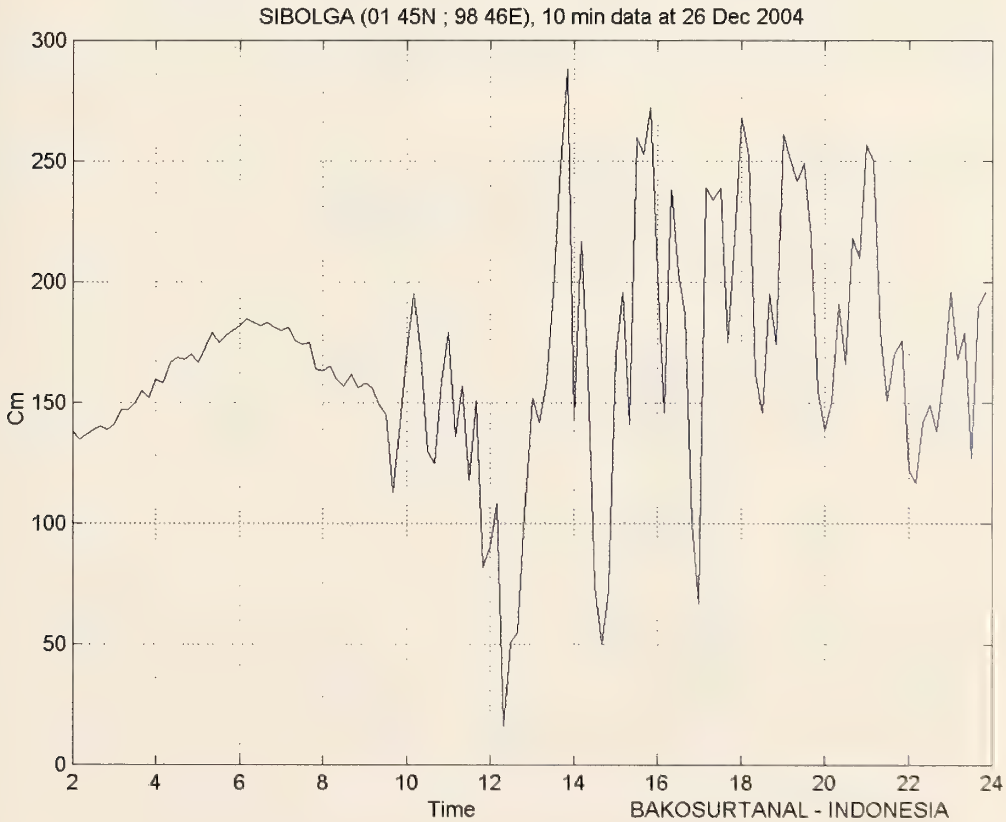

Figure 9. Water-level variations (10-minute interval) at Sibolga, western coast of Sumatra, December 26, 2004 (after Kawata et al., 2005).

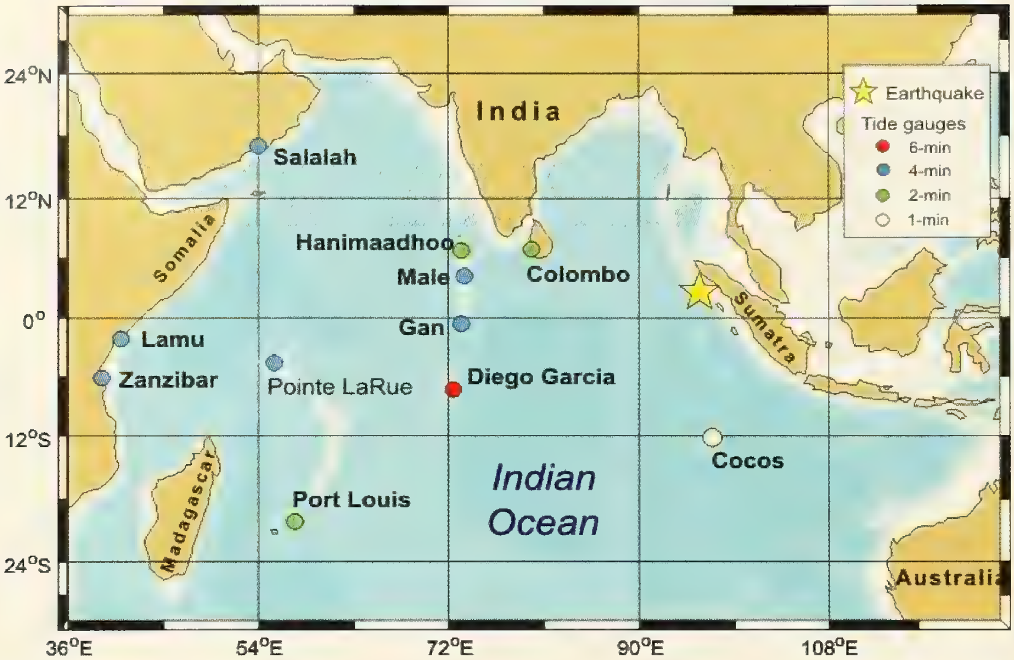

Figure 10. Tide-gauge stations with tsunami records in the Indian Ocean (source: Fisheries and Oceans Canada, 2005).

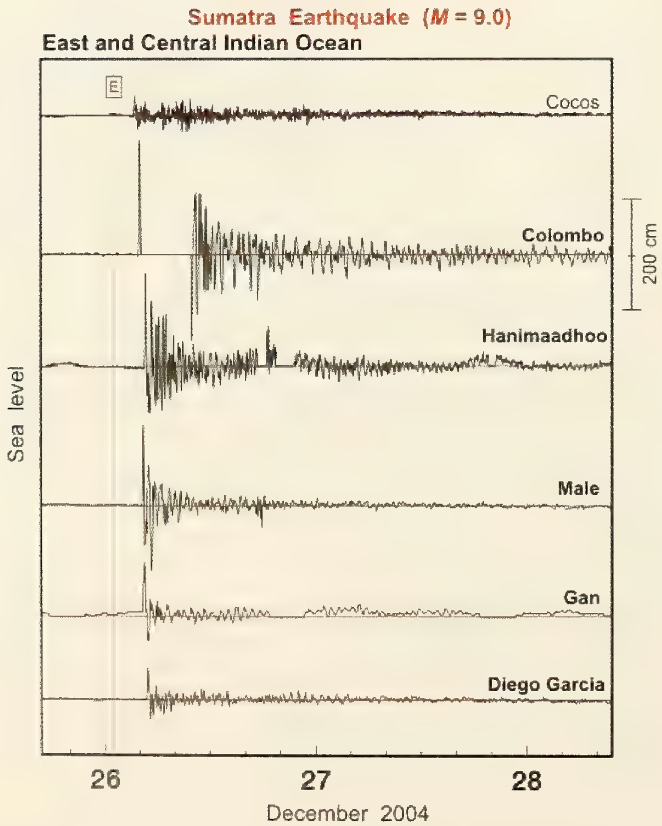

Figure 11. Tide-gauge records of the December 2004 tsunami in the Eastern and Central Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale.

To the west of the epicenter all locations first experienced a wave crest. The first wave, however, was not always the largest in the group; at several sites the second or third wave was the largest. At Zanzibar (Fig. 12) and at tide gauges on the South African coast (Figs. 13 and 14), the largest waves arrived six to eight hours after the first wave, while at Portland, Australia larger waves were seen 9 hours after the first arrival with the largest wave recorded as long as 15 hours after the initial impact (Merrifield et al., 2005).

At most locations the waves continued for hours to days after the initial impact (e.g., Colombo, Hanimaadhoo, Fig. 11), indicating the possibility of wave reflections at an Indian Ocean basin scale (e.g., Van Dorn, 1984). At the inter-regional scale, however,

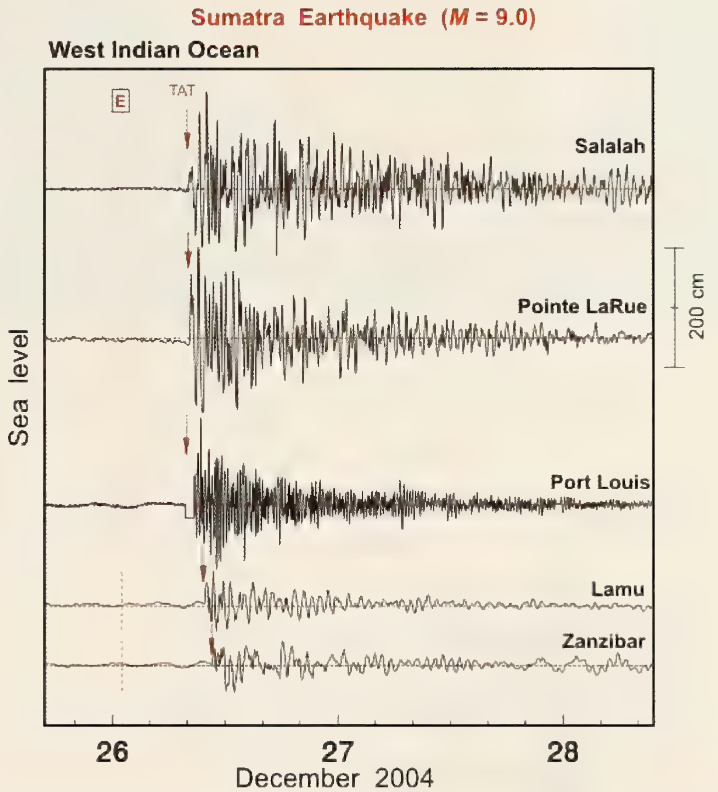

Figure 12. Tide-gauge records of the December 2004 tsunami in the Western Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale.

mid-ocean basin station (e.g., Male, Gan, Diego Garcia) water-level records contained ongoing oscillations which were very small compared to the initial waves (Fig. 12). In the Maldives, the first wave was the largest and most sustained and the atolls were subject to “rapid surges of water rather than the large waves experienced in Thailand and Sumatra” (AusAID, 2005, 3).

By comparison, tide-gauge records from locations as geographically dispersed as Oman (e.g., Salalah, Fig. 12) western Australia, eastern Cape, South Africa (Fig. 14; Merrifield et al., 2005) and around Vancouver Island on the Pacific Ocean west coast (Rabinovich, 2005b), showed oscillations of similar amplitude persisting for one to two days. Such signals probably resulted from resonant water level oscillations, with a period of 20–45 minutes, associated with continental shelf bathymetries.

Figure 13. Tide-gauge stations with tsunami records in South Africa (source: Fisheries and Oceans Canada, 2005).

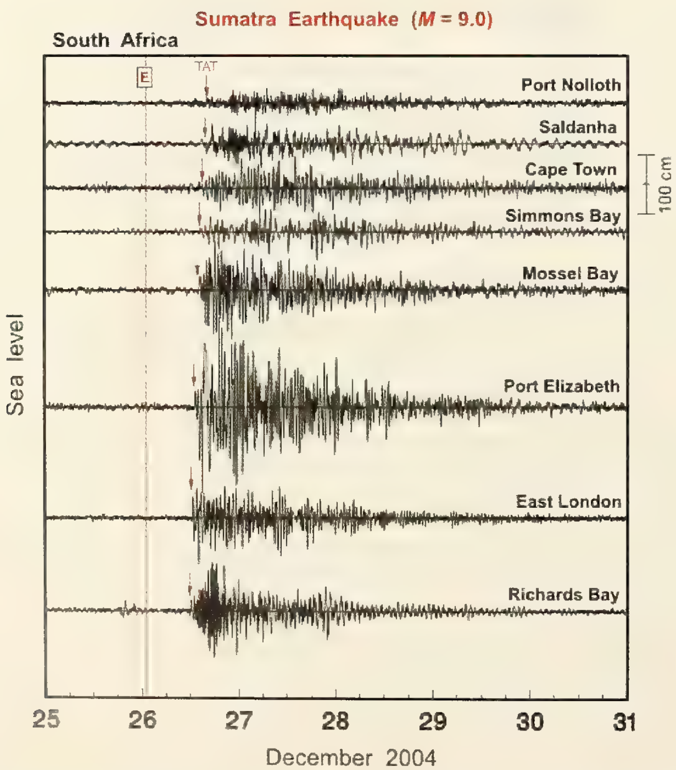

Figure 14. Tide-gauge records of the December 2004 tsunami in South Africa (sources: Farre, 2005; Fisheries and Oceans Canada, 2005). For locations see Figure 13. Note vertical scale.

Relation to Tidal Levels

The tsunami was superimposed on a mixed (diurnal and semidiurnal) tidal signal. In general, the arrival time of the initial tsunami waves coincided with low- or mid-tide. However, in some locations, the arrivals coincided with high tide, as at Vishakpatnam and Chennai, India (NIO, 2005); Langkawi and Penang Islands, Malaysia (Yalciner et al., 2005b), Port Louis, Mauritius and Port Elizabeth, South Africa (Merrifield et al., 2005). On the east coast of Sri Lanka, the tsunami waves coincided with high spring tides and close to the seasonal sea-level maximum but not on the west coast where the tidal phase is opposite to that of the east coast (Merrifield et al., 2005).

Wave Characteristics: Field Measurements

Table 3 consolidates reports on water-level elevations around the Indian Ocean for the December 2004 tsunami. There is considerable difficulty involved in the construction of a standardized, basin-wide assessment of tsunami physical impacts from the December 2004 event. Firstly, the majority of this information is in the form of non-quantitative visual imagery (often of a most dramatic and unpleasant kind) and where semi-quantitative estimates are available they often take the form of unsubstantiated media reports gathered from eyewitnesses often, literally, running for their lives. It is clear for several locations in Sri Lanka and southern India that these reports resulted in the overestimation of tsunami water depths. Secondly, where quantitative measurements are available it is not always clear as to what the heights quoted refer. Typical measures of tsunami characteristics include inundation distances, run-up elevation (the tsunami's height above mean sea level at its limit of penetration inland) and tsunami wave height (Fig. 15). There is frequent confusion between tsunami run-up and tsunami wave height in the various reports available. Run-up statistics are robust but not always easy to ascertain, particularly in the aftermath of such a humanitarian tragedy. They also require field measurements to be related to benchmarks (themselves often buried or destroyed by the event itself) or related to actual water levels where a knowledge of tidal stage is required.

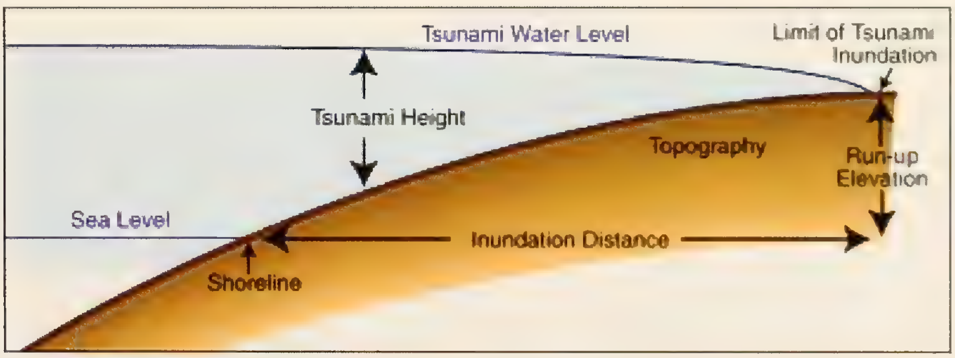

Figure 15. Field survey measurements of tsunami characteristics (from USGS available at http://soundwaves.usgs.gov/2005/03).

Table 3. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
Indonesia			
Banda Aceh, city and island	4.25 – 12.20	NGDC (2005)	R
Kreung Raya	5.10 – 6.71	Tsuji *et al.* (2005)	I
Sabang	3.02 – 6.20	Tsuji *et al.* (2005)	I
Rhiting, Banda Aceh	48.86	Shibayama *et al.* (2005)	I
Aceh Province, west coast	20.00 – 34.90	NGDC (2005)	R
Meulaboh	9.0 – 15.0	Yalciner *et al.* (2005)	I
Simeulue Island	1.3 – 15.0	Yalciner *et al.* (2005), Siberian Division, Russian Academy of Sciences (2005)	I / R
Nias Island	4.5 – 5.3	Siberian Division, Russian Academy of Sciences (2005)	R
Sigli	3.68 – 4.82	Tsuji *et al.* (2005)	I
Medan	1.7 – 2.5	Yalciner *et al.* (2005)	I
Nicobar / Andaman Islands			
Great Nicobar	3.0 – 6.0	Ramanamurthy *et al.* (2005)	R
Car Nicobar	7	Ramanamurthy *et al.* (2005)	R
Little Andaman	5	Ramanamurthy *et al.* (2005)	R
South Andaman	2.9 – 4.5	Ramanamurthy *et al.* (2005)	R
Middle Andaman	1.5	Ramanamurthy *et al.* (2005)	R
North Andaman	1.5 - 5	Ramanamurthy *et al.* (2005)	R
Thailand			
Khao Lak	4.48 – 9.91	Siberian Division, Russian Academy of Sciences (2005)	R
Phuket (W coast)	2.5 – 5.5	Matsutomi *et al.* (2005), Siberian Division, Russian Academy of Sciences (2005)	I / R
Phuket (S coast)	2.5 – 3.5	Matsutomi *et al.* (2005), Siberian Division, Russian	I / R

Table 3 cont. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
Phuket (E coast)	1 – 3.75	Matsutomi *et al.* (2005)	I / R
Kho Phi Phi	4.6 – 5.8	Siberian Division, Russian Academy of Sciences (2005)	R
Malaysia			
Langkawi	2.65	Yalciner *et al.* (2005b)	R
Kedah coast	2.0 – 3.0	NGDC (2005)	R / M
Penang	0.8 – 3.0	Yalciner *et al.* (2005b)	R
India			
Kavali	>5	NGDC (2005)	R / M
Pulicat	3.2	EERI (2005)	R
Chennai (Madras)	1.4 – 2.8	Ramanamurthy *et al.* (2005), EERI (2005)	R / M
Kovalam	4.3	EERI (2005)	R
Kalapakkom	4.1	EERI (2005)	R
Periakalapet	3.9	EERI (2005)	R
Puttupattnam, Ponditcherry	2.6	EERI (2005)	R
Devanaanpattinam	2.5	EERI (2005)	R
Perangipettinam	2.8	EERI (2005)	R
Tarangambadi, Karaikal	4.4	EERI (2005)	R
Nagappattinam	3.9 – 5.2	Ramanamurthy *et al.* (2005), EERI (2005)	R / M
Vedaranniyan	3.6	EERI (2005)	R
Thiruvanaanthapuram (Trivandrum)	1.5 – 2.0	DOD (2005)	R
Kollam (Quilon)	2.0 – 5.0	DOD (2005)	R
Alappuzha (Aleppey)	1.5 – 2.5	DOD (2005)	R
Kochi (Cochin)	2.0 – 2.5	DOD (2005)	R
Kozhikode (Calicut)	1.5 – 2.0	DOD (2005)	R

Table 3 cont. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
Sri Lanka			
Kuchchavelli	>3.70	USGS (2005d)	I
Mankerni	>2.00	USGS (2005d)	I
Kalmunai	4.75 – 5.0	USGS (2005d), Headland (2005b)	I / R
Yala	4.5 – 11.3	USGS (2005d), Sato *et al.* (2005)	I / R
Hambantota	8.8 – 11.0	Sato *et al.* (2005), Headland (2005b)	I / R
Waligama	4.86	Kawata *et al.* (2005)	I
Unawatuna	3.3	Sato *et al.* (2005)	I
Galle	3.24 – 6.03	Kawata *et al.* (2005)	I
Galle	10.0 – 15.0	NGDC (2005)	R / M
Hikkaduwa	3.4 – 4.73	Sato *et al.* (2005), Kawata *et al.* (2005)	I / R
Kahawa	4.08 – 10.04	Kawata *et al.* (2005)	I
Ambalagoda	4.72	Kawata *et al.* (2005)	I
Bentota / Beruwala	2.35 – 5.0	Kawata *et al.* (2005), Headland (2005a)	I / R
Panadura	3.34 – 5.59	Kawata *et al.* (2005)	I
Moratuwa	3.8 – 4.4	Kawata *et al.* (2005)	I
Colombo	2.0 – 2.7	Headland (2005a), Sato *et al.* (2005)	I/ I
Negombo / Waikkala	1.6 – 2.7	Sato *et al.* (2005)	I
Vennapuwa / Marawila	1.8 – 2.3	Sato *et al.* (2005)	I
Maldives			
Keyodhoo	2.18 – 2.89	Siberian Division, Russian Academy of Sciences (2005)	R
Muli / Rinbudhoo	2.11 – 3.18	Siberian Division, Russian Academy of Sciences (2005)	R
Gemendoo	2.71 – 3.17	Siberian Division, Russian Academy of Sciences (2005)	R
Fanadoo / Kaddhoo	1.28 – 4.43	Siberian Division, Russian Academy of Sciences (2005)	R
Addu Atoll	1.31 – 2.08	Siberian Division, Russian Academy of Sciences (2005)	R

Table 3 cont. Water level elevations around the Indian Ocean reported from the tsunami of 26 December 2004.

Location	Height of Tsunami Run-up / Inundation (m)	Source	Comments R = run-up I = inundation M = media report
Seychelles			
Mahé	1.6 – 4.4	Jackson *et al.* (2005)	I
Praslin	1.8 – 3.6	Jackson *et al.* (2005)	I
Somalia			
Bargaal	5	Fritz and Borrero (2005)	R
Xaafuun	4.5	Fritz and Borrero (2005)	R
Foar	5.0 – 7.0	Fritz and Borrero (2005)	R
Bandarbeyla	5.0 – 8.0	Fritz and Borrero (2005)	R
Eyl	5.0 – 9.0	Fritz and Borrero (2005)	R

The measurement of tsunami wave height clearly varies with distance from the shoreline, given the decay of tsunami height with distance inland and the varying frictional resistances from topography, vegetation and buildings to tsunami waves for impacts at the same distance from the shore. There is also a need to distinguish between the highest point reached by breaking waves on exposed coasts, marked by debris lines and bark and leaf stripping on standing trees, and the record of still water levels, often marked in more sheltered settings by water lines on buildings and other structures. Thirdly, it is clear that all these characteristics varied greatly at a regional-to-local level with coastline orientation, bathymetry (e.g. presence / absence of submarine canyons), coastal geology and topography (e.g., headlands v. embayments) causing significant variations in wave focussing, shoaling and refraction, and with coastal plain topography, ecology and settlement patterns (including coastal defence structures), influencing penetration distances and styles of inundation. Finally, effects were further mediated at the small scale with the passage of the tsunami waves over, around and through individual buildings and infrastructure. The view that the loss and degradation of natural ecosystems at the coast under severe human exploitation exacerbated tsunami impacts has been widely promulgated (e.g., UNEP, 2005). A number of short notes have argued that the removal of sand dunes (e.g., at Yala, Sri Lanka (Gibbons et al., 2005)) and mangrove forest (e.g., at Cuddalore, India (Danielsen et al., 2005) and throughout southern Sri Lanka (Dahdouh-Guebas et al., 2005)), and the destruction of coral reefs though coral mining and blast fishing (e.g., between Hikkaduwa to Akuralla, Sri Lanka (Fernando et al., 2005)), locally increased damage and loss of life by creating low resistance pathways to tsunami waves, associated with greater wave heights and increased penetration inland. Although such claims are supported in general terms by mathematical modelling (e.g. Massel et al., 1999), there has been, inevitably, a strong reliance on scattered, largely qualitative observations; a re-appraisal six months after the tsunami concluded that ‘evidence so far collected only weakly supports the assertion that coastal wetlands can act as a “green barrier” to protect the coastline and its communities’ (Wetlands International, 2005). Furthermore, it has also been argued that where tsunami impacts were particularly severe, the buffering capacity of natural ecosystems was exceeded and did not influence flow depths or inundation distances (Baird et al., 2005).

In the near field, many locations suffered catastrophically high water levels (Table 3). It appears that two tsunami wave crests, from the north and southwest, converged at the northwestern tip of Sumatra. Wave scour and subsidence set back the shoreline at Banda Aceh by up to 1.5 km; eroded sand was deposited in tsunami overwash-type deposits over 70 cm thick in places (USGS, 2005c). Sixty-five kilometers of land between Banda Aceh and Lhoknga were flooded. Flow depths exceeded 9 m at Banda Aceh and inundation reached 3–4 km inland. An inundation height of 48 m has been recorded at Rhiting, Banda Aceh from damage to vegetation and probably records maximum wave height (Shibayama et al., 2005). At Lhoknga, flow depths were in excess of 15 m and tsunami run-up reached 31 m (Borrero, 2005). Elsewhere in this area run-up elevations of 15–30 m were mapped along a 100 km stretch of coastline south to Kreung Sabe (USGS, 2005a), with a maximum recorded run-up to 34.9 m (Tsuji et al., 2005). These high run-ups appear in part to be due to the rapid arrival of the second and third waves after the

initial impact. These subsequent waves overrode the first wave and thus suffered reduced frictional loss allowing greater landward penetration (USGS, 2005c). Further south, at Meulaboh, tsunami run-up continued to exceed 15 m and inundation reached 5 km inland. Offshore, on Simeulue Island, maximum flow depths were 3 m, inundation reached up to 2 km inland and tsunami run-up was also up to 15 m. On the Thai coast, water levels approached 5 m and at Khao Lak, where the town was completely destroyed, almost reached 10 m (there is no readily available information on water levels experienced further north in Myanmar). By comparison, maximum tsunami run-up was only half the 15 m figure on the eastern coast of northern Sumatra, as a result of sheltering effects and shoaling and refraction in the shallow entrance to the Strait of Malacca. The tsunami did not reach Medan until 4 hours after the earthquake, maximum water depths were ca. 1.7 - 2.5 m and inundation distances were less than 1 km (Yalciner et al., 2005a). Similarly, along the west coast of Peninsula Malaysia, flow depths were generally less than 3 m and inundation distances less than 100 m, except where there was penetration into estuaries; the southern limit of the tsunami waves on this coastline was 4°N (Yalciner et al., 2005b).

After Sumatra, the most heavily impacted coastline was that of Sri Lanka. There was a strong patterning to impact at the island scale, with tsunami heights and run-up increasing on the east coast to the south and on the south coast to the east. Peak levels exceeded 11 m in the southeast of the island and levels close to 5 m were reached almost as far west and north as Colombo. At the village of Peraliya, near Hikkaduwa, a 10 m high wave, derailed the engine and eight coaches of the Colombo – Galle express, carrying the train 50 m inland and resulting in over 1500 fatalities. Tide gauge water level variations at Colombo were exceptionally high (Fig. 11) yet this was by no means a severely impacted part of the island. Inundation distances on Sri Lanka reached 1 km where position (southeast coast) and topography (embayments between rocky headlands) concentrated wave attack. At Mankerni on the northeast coast, where impact was modest and inundation depths were less than 2 m, an area 1 m deep and 20–30 m wide was eroded, the sand being deposited 50 m inland as a 10 cm thick tsunami deposit tapering to 2 cm thick at 150 m inland (USGS, 2005d).

On the eastern coast of India, run-up levels typically approached 3–4 m, increasing to over 5 m at Nagappattinam where inundation penetrated 750 m inland. Further south on this coast, run-up levels declined as the coast was effectively sheltered on the leeward side of Sri Lanka. The west coast of India experienced typical run-up elevations of 1.5 to 2.5 m, with local maxima of 5 m.

The strong E–W directionality of the tsunami led to run-up elevations in excess of 4 m in the Maldives and of 4.5 to 9 m on the rocky coastline of Somalia. However, the large-scale refraction of the tsunami around Sri Lanka and southern India led to a spreading of the wave crest across the SW Indian Ocean and thus a reduction in wave height in this direction (Table 3). The diminution of the tsunami to the south from Hanimaadhoo in the northern Maldives (ca. 7°N) to Diego Garcia (7°S) is instructive (Fig. 11). Further south and further west, in Mauritius for example, the signal (Fig. 12) was more one of localized flooding on a high tide rather than the kind of destructive wave action seen in Southeast Asia.

WHAT NEXT: THE MARCH 2005 EARTHQUAKE AND BEYOND

As it now appears that the entire rupture zone slipped in December 2005, the accumulated strain from the subduction of the Indian Plate beneath the Burma microplate has been released, leaving no immediate danger of a comparable tsunami on this segment of the plate boundary. Current estimates of plate convergence across this area suggest that in the vicinity of Port Blair, Andaman Islands a renewal time of 800-1000 years would be required to develop the 10 m of release observed (Bilham et al., 2005), although the much faster convergence rates near the 2004 epicenter suggest a correspondingly shorter interval between major earthquakes of 400 years. However, large earthquakes are often coupled (e.g., Kobe: Toda et al., 1998, Izmit: Stein et al., 1997) as failures spread stresses to other structures in the region. Following the December 24, 2004 rupture, McCloskey et al. (2005) drew attention to increased earthquake risk on both the southerly continuation of the Sunda arc and on the neighboring vertical strike-slip fault system which runs through the island of Sumatra. The threat of failure in the latter remains.

However, it was not unexpected when the Sunda megathrust ruptured again just three months later at 2.1°N under the islands of Simeulue and Nias (160 km southeast of the December 2004 epicenter). The earthquake, with a moment magnitude of 8.7, commenced at 16:09:36 UTC on March 28, 2005 with a rupture-zone length of 300 km (Lay et al., 2005). Ground movements resulted in ca. 1 m of subsidence on the coast of Kepulauan Banyak as well as 1 m of uplift on the coast of Simeulue. At least 1000 people were killed, 300 injured and 300 buildings destroyed on Nias where tsunami run-up heights of 2 m were reported. One hundred people were killed, many injured and several buildings damaged on Simeulue where a 3 m tsunami damaged the port and airport. Two hundred people were killed in Kepulauan Banyak and tsunami run-up heights of 1 m were experienced on the Sumatran coast at Singkil and Meulaboh (USGS, 2005b). However, the tsunami was directed in a southwesterly direction and thus dissipated more harmlessly across the Indian Ocean than the December 2004 waves. Thus, although tsunami wave heights were clearly recorded after the March 2005 event, they were of unremarkable amplitude: ca. 40 cm on Panjang, Indonesia; ca. 25 cm at Colombo, Sri Lanka; and 40 cm on Hanimaadhoo, 18 cm at Male and 10 cm at Gan in the Maldives (Fig. 16; USGS, 2005b). By the East African coast there was almost no signal at all (Fig. 17). This pattern is likely to have similarly characterized the tsunami associated with the great Sumatran earthquake of 1833 (Fig. 18; Cummins and Leonard, 2005).

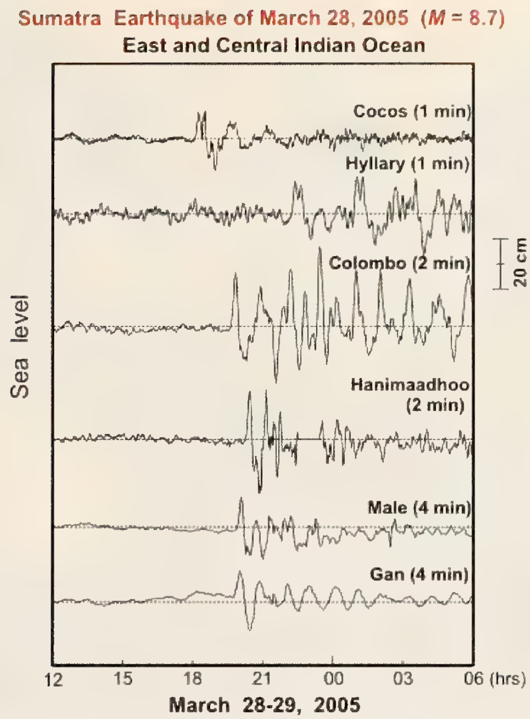

Figure 16. Tide-gauge records of the March 2005 tsunami in the Eastern and Central Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale and compare to Figure 11.

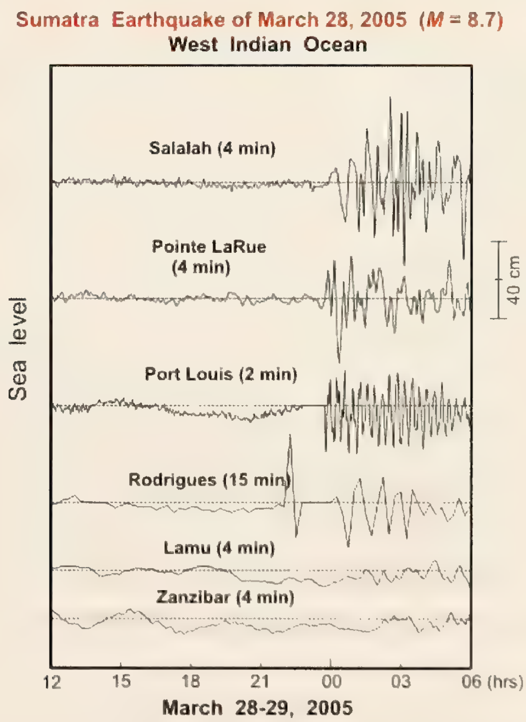

Figure 17. Tide-gauge records of the March 2005 tsunami in the Western Indian Ocean (source: Fisheries and Oceans Canada, 2005). For locations see Figure 10. Note vertical scale and compare to Figure 12.

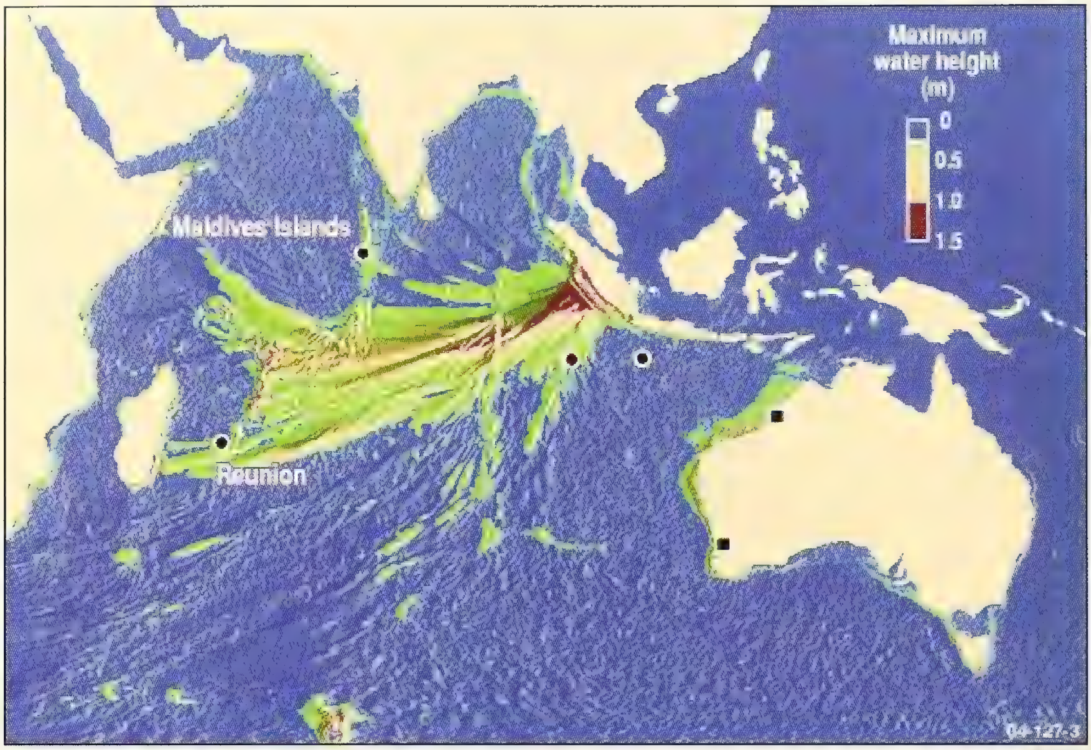

Figure 18. Calculated maximum amplitude of the tsunami caused by the 1833 Sumatra earthquake. Most tsunami energy was directed in a southwesterly direction into the open Indian Ocean (Numerical modelling performed by David Burbidge of Geoscience Australia; http://www.ga.gov.au/ausgeonews/ausgeonews200503/tsunami.jsp

This second large earthquake event has now increased stresses to the south of its epicenter. Nalbant et al. (2005) have identified the area beneath the Batu and, particularly, the Mentawai Islands as being at high risk of earthquake and tsunami generation. In the case of the latter island group, the megathrust has not ruptured under the most northerly island of Siberut since 1797, while at Sipura and Pagai, a few meters of slip and 10 m of slip were experienced in 1797 and 1833 respectively. Events similar to the 1833 event appear to have a 230-year cycle and thus the area is approaching the later stages of this cycle. This supposition is confirmed by field observations and stratigraphic analysis of seven microatolls, five from the islands and two from the mainland coast, which indicate that the Mentawai Islands have been submerging at rates of 4-10 mm a^{-1} over the last four or five decades, while the mainland has remained relatively stable (Zachariasen et al., 2000). Similar rates of subsidence preceded the 1833 earthquake and tsunami (Zachariasen et al., 1999). Were the next failure to be of comparable magnitude to that of 1833 then further tsunami activity could be a possibility (Nalbant et al., 2005).

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TSUNAMI IMPACTS IN ACEH PROVINCE AND NORTH SUMATRA, INDONESIA

BY

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ABSTRACT

The huge earthquake and resulting tsunami which occurred on December 26, 2004 off the west coast of Sumatra resulted in regionally variable patterns of impact in and around the Indian Ocean basin. The coast of Sumatra was close to the earthquake epicenter and was the first to be struck, within one hour of the event. A collaborative expedition between the Khaled bin Sultan Living Oceans Foundation, Reef Check International and IUCN (World Conservation Union) to the northwest coast of Sumatra and Aceh Province, Indonesia, was conducted in October 2005.

Reef surveys were conducted using two methods: Manta Tow and the Reef Check Plus protocol. A total of 9 sites (8 offshore island sites and 1 mainland Aceh site) were surveyed over a distance of 650 km. Typically tsunami damage was observed as overturned coral colonies and tree debris on the reef. Over half of the reefs surveyed indicated that there had been no tsunami damage and only 15% of the sites surveyed indicated a high level of damage. However, even in areas where severe tsunami damage was recorded and corals were killed as a result of the event, there were still large areas of intact reef present, which will be able to repopulate the damaged reef in the future. Similar post-tsunami surveys in Thailand suggest that full recovery of these reefs should occur within the next 5-10 years.

There was evidence that the earthquake caused both uplift and subsidence of some islands. These processes have resulted in three impacts on reefs: 1) extensive mortality of uplifted reef-flat corals, 2) the bringing of reef-front corals into the reef-flat zone and 3) the relocation of reef-flat communities to the reef-front. Both uplift and subsidence therefore have implications for near-future reef ecosystem dynamics in the region.

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INTRODUCTION

On December 26, 2004 an earthquake measuring 9.3 in magnitude (Bilham, 2005) occurred at latitude 3°N, off the west coast of Sumatra where the northward moving Indo-Australian plate is subducted below the continental Eurasian plate. This earthquake was the most severe event since the Alaskan earthquake of 1964 and was the second largest since modern seismographic recording began over a hundred years ago. The energy it released was as much as all the global earthquakes combined between 1976 and 1990. This huge earthquake triggered tsunami waves, which caused devastation throughout the Indian Ocean basin. The coast of Sumatra was the first to be struck, within one hour of the event. The tsunami waves reached Sri Lanka and India in 2-3 hours, Seychelles and Mauritius in 7 hours, East Africa in 9 hours and South Africa in 11-14 hours. This tsunami event was the most catastrophic such event in recent history resulting in the deaths of over 300,000 people (Spencer, 2007).

The effects of hurricanes and cyclones on coral reefs have been well documented for more than 20 years (e.g. Woodley et al., 1981; Bythell et al., 2000) but there are no such reports on the effects of tsunami waves on coral reefs. At the International Coral Reef Initiative's (ICRI) 10th Anniversary meeting in the Seychelles in April 2005, a review of post-tsunami reef damage assessments was made. The review revealed that numerous reef surveys had been conducted throughout the Indian Ocean (e.g. Thailand, Seychelles, Maldives, Sri Lanka) to observe coral-reef damage following the December 2004 tsunami, but there was an evident lack of surveys along the west coast of Sumatra, the coastline closest to the epicenter of the earthquake. Northwest Sumatra experienced very severe terrestrial tsunami damage; water inundation reached 3-4 km inland and wave scour and coastal subsidence set back the shoreline by 1.5 km (Borrero, 2005). The aim of this expedition was to survey a 650 km stretch of the west coastline and offshore islands of Sumatra, Indonesia, from Sibolga to Banda Aceh (in Aceh Province) (Fig. 1) in order to document the state of the reefs in this area following the December 2004 tsunami and to fill a gap in the knowledge of the impacts of the tsunami around the Indian Ocean basin.

REEFS OF NORTH SUMATRA

Sumatra, with a coastline of approximately 4,500 km (excluding offshore islands) is one of the least known Indonesian islands with regard to coral reef distribution (Tomascik et al., 1997). Extensive fringing reefs, approximately 200 m in width, occur in the north, around Aceh, along the west coast, and around the northern islands, especially Pulau Weh (Tomascik et al., 1997). An 85 km long barrier reef is reported 20 km off the coast of Aceh, but this is a submerged or drowned system 13-20 m below the surface, and the degree of active coral growth here is unknown (Spalding et al., 2001). Sea surface temperature along Sumatra's coastline ranges from 26°-30°C and salinity ranges from 33-34 ppt (Tomascik et al., 1997). Indonesia, specifically eastern Indonesia, is known to be the world's centre of coral biodiversity, exhibiting 581 species within 82 genera (Veron, 2000). Coral diversity in Sumatra has not been documented.

Figure 1. Map of Aceh Province, Sumatra, Indonesia illustrating expedition itinerary 17-31 October 2005. Numbers represent site numbers as defined in Table 1. Red dot indicates approximate December 26, 2004 earthquake epicenter.

Table 1. Regions and survey sites as shown on Figure 1.

Region	**Site Name**	**Site Number on Fig. 1**
Banyak	Pulau Bangkaru	1
	Pulau Baleh	2
	Pulau Bagu	3
North Aceh coast	North Aceh coast	4
Northern Islands	Pulau Nasi Besar	5
	Pulau Buro	6
	Pulau Weh	7
	Pulau Rondo	8
	Pulau Bunta	9

METHODS

Two primary survey methods were used during the expedition: the Manta Tow method and the Reef Check Plus protocol (Hodgson et al., 2005). The Manta Tow method is a rapid visual assessment, enabling a very large area to be surveyed in short period of time. It involved a snorkeller holding onto a 'Manta Board' being towed behind a boat (English et al., 1997). The snorkeller recorded a visual assessment of the reef observed (i.e., percentage cover of live coral, rock, rubble, etc.). The Reef Check Plus methods focussed on a much smaller area of reef but the surveys were more detailed, surveying the benthic, fish and invertebrate communities along a 100 m transect line. Typically, shallow (3-5 m) and deep (8-10 m) Reef Check Plus surveys were conducted at each site. These two methods have various advantages and disadvantages but by employing them in combination the advantages were maximized and the disadvantages were minimized. These two survey methods enabled general characteristics of the reefs of north Sumatra to be recorded. In addition to these standard methods, particular note was made of tsunami damage on the reefs. Tsunami damage was identified as:

1) Mechanical damage: Broken pieces of coral
2) Overturned / rolled coral
3) Sedimentation: Run-off from land being washed onto reef

The level of tsunami damage observed was also recorded as 'low', 'medium' or 'high' by estimating the number of overturned and/or broken coral pieces observed during each Manta Tow. 0–10 pieces indicated 'low' tsunami damage, 10-30 pieces indicated 'medium' tsunami damage and 30+ pieces indicated 'high' tsunami damage. A 'piece of coral' was defined as being less than 15 cm in diameter along its longest axis.

In total, nine offshore island sites (Karang, Bangkaru, Baleh, Bagu, Nasi Besar, Buro, Rondo, Weh and Bunta) and one mainland site (north coast of Aceh Province, east of Banda Aceh city) were surveyed (Fig. 1).

RESULTS

Reef Characteristics

Benthic survey results have been combined into three groups: Banyak region, north coast of Aceh and northern islands (Table 1; Fig. 2). Banyak region reefs were shown to be dominated by hard coral cover (39% cover) and rock (29% cover) with moderate amounts of rubble and sand. Recently killed coral represented only 0.1% cover in the Banyak region. Reefs of the northern island were dominated by rock (37% cover) and rubble (29% cover), followed by hard coral cover (25% cover). Recently killed coral represented only 0.3% cover in the northern islands. Reefs of the north Aceh coastline showed marked differences compared to the other two areas. Here the reef was dominated by rock (35% cover), and although hard coral cover was identical (25% cover) to that recorded in the northern islands, soft corals were also evident in the coral community (11% cover). The north Aceh coastline displayed a higher proportion of recently killed coral (3% cover) but a much lower proportion of rubble (11% cover) compared to the other two sites.

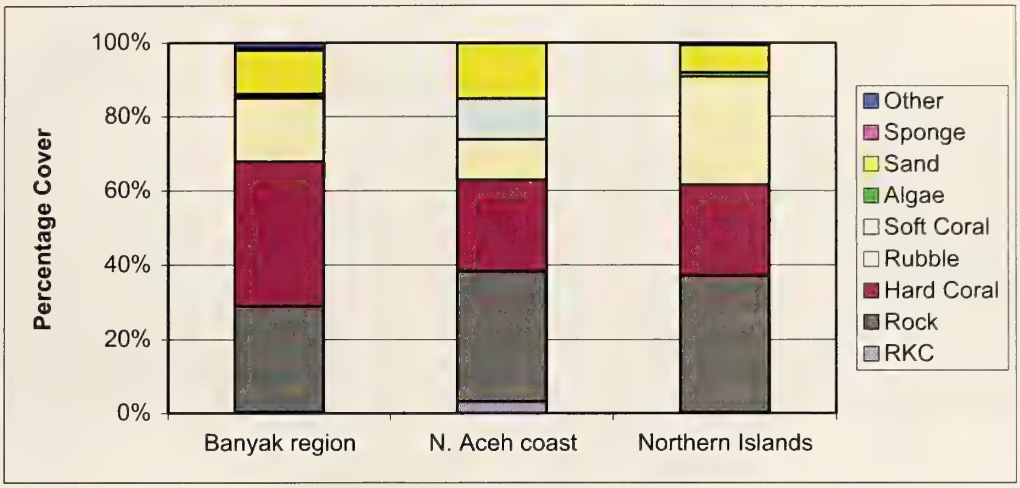

Figure 2. Summary of percentage cover by benthic category for three regions of Aceh. Results from Reef Check surveys (RKC = Recently Killed Coral).

Earthquake Damage: Banyak Region

Two major earthquakes occurred in the waters offshore of Aceh in December 2004 and March 2005. Earthquake damage was observed at Pulau Bangkaru (uplift), Pulau Baleh (subsidence) and Pulau Bagu (subsidence) in the Pulau Banyak group. A large area of largely intact (little erosion was observed and most branching corals were unbroken) reef-flat, approximately 500 m in width, had been completed raised by approximately +2 m, killing the corals through subaerial exposure (Fig. 3). The corals had not yet been eroded and could easily be identified to genus level, indicating that the uplift was recent. Many dead *Porites* microatolls were present, as were colonies of branching *Acropora* and *Pocillopora* and many empty giant clam shells.

In contrast, terrestrial observations at the islands of Baleh and Bagu, two islands which lie less than one kilometer apart from one another in the Banyak group (Fig. 1, sites 4 and 5) indicated that subsidence had occurred as a direct result of an earthquake. Terrestrial tsunami damage was highly evident. Low-lying vegetation close to the shore was brown and dead (Fig. 4a), presumably as a result of salt-water inundation and many buildings had been removed from the coastline (Fig. 4b).

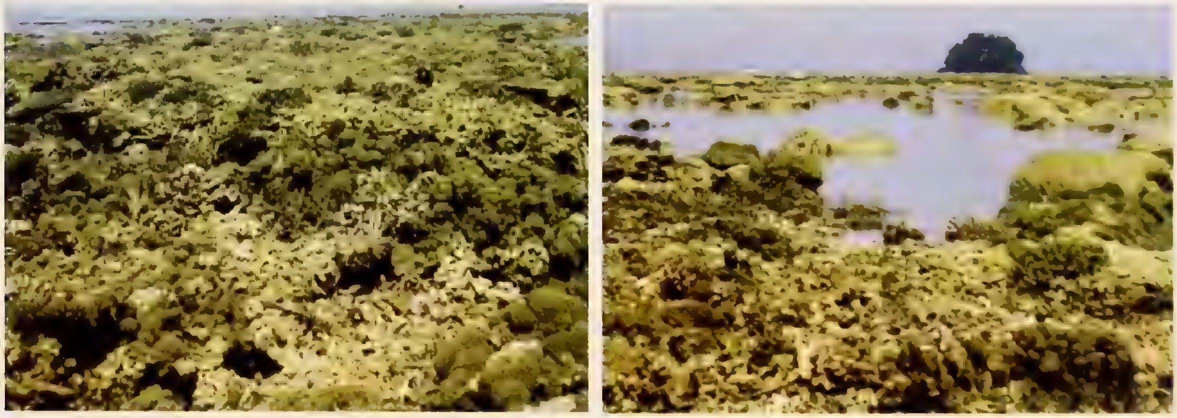

Figure 3. Uplifted reef at Pulau Bangkaru, observed on October 19, 2005.

Figure 4. Terrestrial tsunami damage at Pulau Baleh showing (a) dead vegetation along the coast and (b) foundations of buildings that have been washed away by the tsunami wave.

The houses remaining along the seafront were noted to all have a clear brown mark at approximately 80 cm height up their walls (Fig. 5). It seemed strange for this water mark to remain so clear 10 months after the tsunami hit, but having spoken to the islanders it became apparent that this was an effect of the earthquake as opposed to the tsunami wave. The island had subsided as a result of the December 2004 earthquake and as a result, the buildings along the seafront are now inundated with up to 1 m of water during each high tide. Presumably the coral reefs surrounding these islands must also have submerged by a similar amount, converting intertidal reef-flat communities into subtidal ones.

Tsunami Damage: North Coast of Aceh Province

The north coast of Aceh, approximately 13 km east of the town of Banda Aceh, exhibited differing degrees of tsunami damage. All surveys were shallow (3-5 m depth) as the reef did not extend below 5 m water depth, but instead gave way to a sandy bottom. The five sites were found to harbor different types of reef communities and exhibited varying degrees of tsunami damage. Manta Tows indicated that tsunami damage was generally ‘low’ at this site with only 4 out of 39 tows indicating ‘high’ damage and 4 out of 39 tows indicating ‘medium’ damage. Rock was estimated to dominate the substrate, representing 44% cover although live coral cover represented an average of 31% and rubble represented 25% cover. The first Reef Check Plus survey was conducted at the headland ‘Ug Batukapal’, a site identified by the Manta Tow team as having good live coral cover. Indeed the substrate transect was dominated by live coral cover (32%) with a moderate amount of rock and sand (25% cover for each). Interestingly, soft corals made up 14% of the total substrate at this site, a category that had been little observed elsewhere.

Figure 5. Water mark on house on Pulau Baleh; mark represents the daily height of water inundation at high tide. This house is approximately 70 m inland.

The survey conducted at the headland adjacent to 'Ug Batukapal' indicated a very different type of reef community. Here the reef was composed of large flat solid plates of limestone 'coral pavement' (50% of total transect) interspersed with soft corals; specifically of the genus *Sinularia* and whip corals (Fig. 6a and b). There were few hard corals (hard coral cover was only 6%) compared to the number of soft corals present, which accounted for 27% of the total substrate along the transect line.

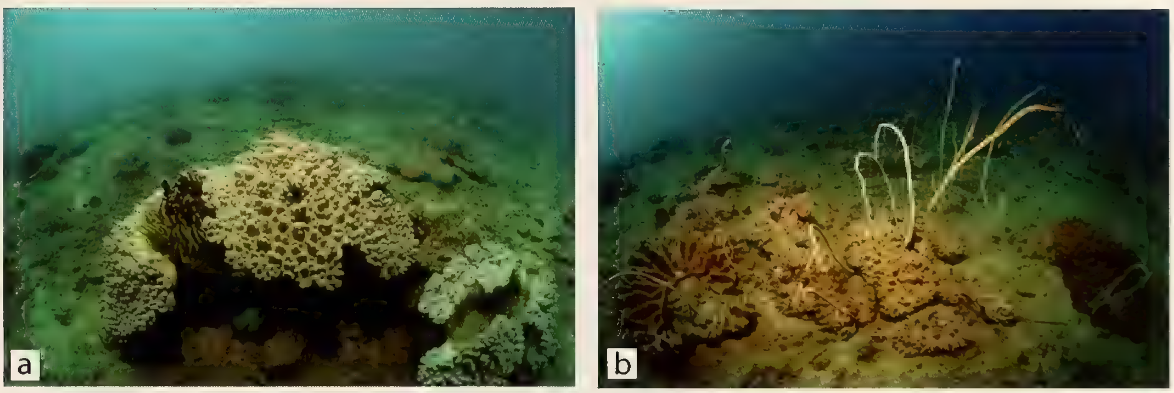

Figure 6. Reef dominated by coral pavement interspersed with soft corals at 3 m water depth: (a) *Sinularia* spp. (b) *Sinularia* spp. and delicate sea whips *Junceella fragilis*, north Aceh coast, October 27, 2005.

Moving eastward, two surveys were conducted in a large bay area. One of these surveys was of particular interest as it identified considerable tsunami damage, specifically overturned dead *Acropora* tables (Fig. 7), overturned live *Porites* spp. (Fig. 8) and tree debris (Fig. 9).

Figure 7. Overturned dead *Acropora* sp. table at 4 m water depth on the north coast of Aceh Province, October 27, 2005.

Figure 8. Overturned live *Porites* sp. colony at 4 m water depth on the north coast of Aceh Province, October 27, 2005.

Figure 9. Tree debris on the reef at 5 m water depth; north coast of Aceh Province, October 27, 2005.

The reef was characterised by 31% rock and equal proportions of live coral cover and rubble (21% each). Moving further east, the final survey in this area displayed minimal signs of tsunami damage. Although one tree branch was observed on the reef, no coral had been killed, broken or overturned and the reef displayed large stands of healthy blue coral *Heliopora coerulea* (Fig. 10) and *Porites* spp. Live coral cover accounted for 35% of the substrate.

Figure 10. Large stands of healthy blue coral *Heliopora coerulea* at 3 m water depth off the north coast of Aceh Province, October 27, 2005.

Tsunami Damage: Northern Islands

Pulau Weh (marked by the main town ‘Sabang’ on Fig. 1) lies off the north coast of Aceh Province and is the largest (153 km^2) and most populated (population ~28,500) of the northern offshore islands. A visit ashore on the north coast of Pulau Weh confirmed that there had been significant impacts from the tsunami wave on land (Fig. 11).

Figure 11. Lumba Lumba dive shop on Pulau Weh; arrow indicates maximum height of wave action (~5 m above sea level) on December 26, 2004.

A single site was surveyed on the southwest coast of Pulau Weh. Manta Tows indicated that there was 44% rock cover and 23% live coral cover with the rest of the substrate being split equally between rubble and sand. Half the tows indicated ‘low’ tsunami damage and half indicated ‘medium’ tsunami damage. The Reef Check survey at 6 m depth indicated that although 38% of the substrate was live coral cover, this figure was equalled by rubble cover. Rock represented 22% of the transect line. Although some patches of reef were intact (Fig. 12), there was clear evidence of tsunami damage on the reef along this transect.

Many massive *Porites* spp. colonies had been split into vertical fragments or overturned (Fig. 13a and b) and large colonies of the blue coral *Heliopora coerulea* had been overturned and shattered into small pieces (Fig. 14a and b).

Figure 12. Intact coral reef at 4 m water depth clearly showing healthy *Porites* spp. (far left and far right) and *Heliopora coerulea* (centre front) colonies along transect line at Teluk Balohan, Pulau Weh, October 28, 2005. Transect line shown back left.

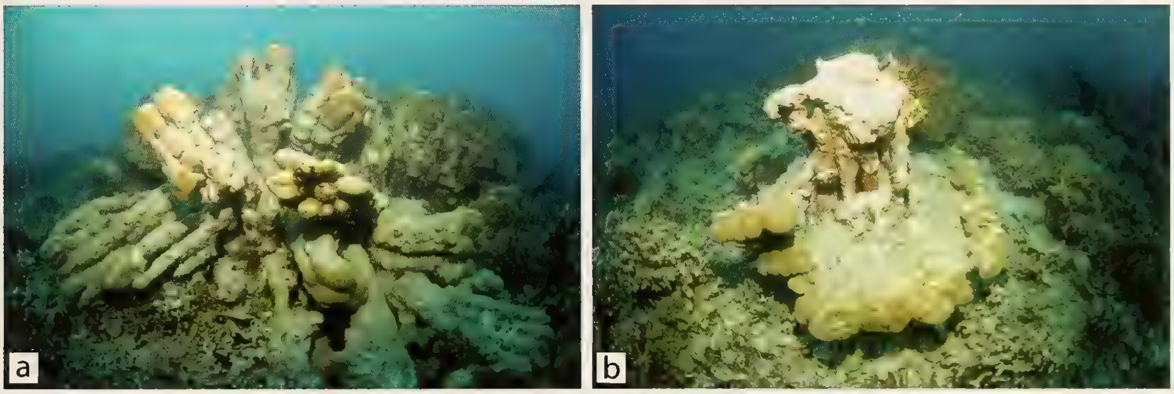

Figure 13. (a) Split *Porites* sp. colony and (b) overturned *Porites* sp. colony at 4 m water depth, Teluk Balohan, Pulau Weh, October 28, 2005.

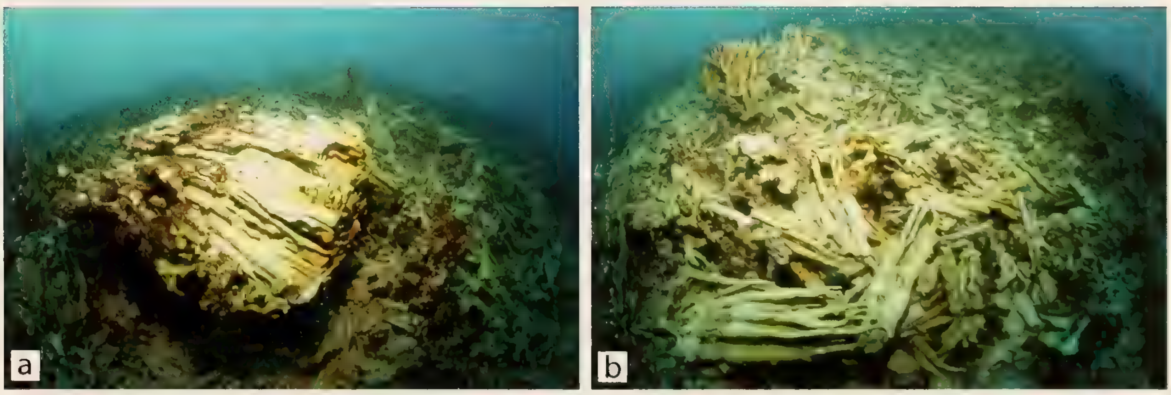

Figure 14. (a) Overturned blue coral *Heliopora coerulea* and (b) shattered blue coral *Heliopora coerulea* at 3 m water depth, Teluk Balohan, Pulau Weh, October 28, 2005.

Pulau Rondo (Fig. 1, site 13) is a small, uninhabited island situated north-west of Pulau Weh and is the most northerly point of Indonesia. Manta Tows and shallow and deep Reef Check Plus surveys were conducted at two sites at Pulau Rondo; one off the west coast and one off the east coast. The Manta Tows indicated that some areas displayed 'low' tsunami impact and some areas displayed 'high' tsunami impact, but the majority showed 'medium' tsunami impact. Live coral cover was estimated to be 50%, with a further 15% of the substrate being reported as 'recently killed coral'.

On the west side of Pulau Rondo, the shallow Reef Check survey was dominated by rock (41%), with a reasonable amount of live coral cover (37%). The deep site on the west side of Pulau Rondo showed some tsunami damage, specifically overturned

Acropora spp. tables, both alive (Fig. 15) and dead (Fig. 16a and b) and overturned *Porites* spp., but the majority of the reef was unaffected (Fig. 17). Live coral cover was 39%, although this figure was equalled by the proportion of rubble along the transect line.

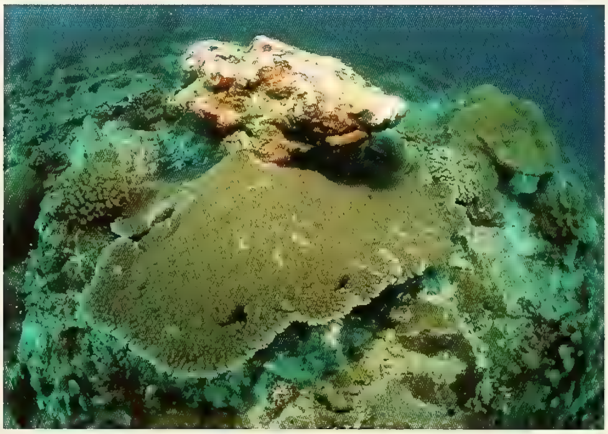

Figure 15. Overturned live *Acropora* sp. table at 10 m water depth at Pulau Rondo, October 29, 2005.

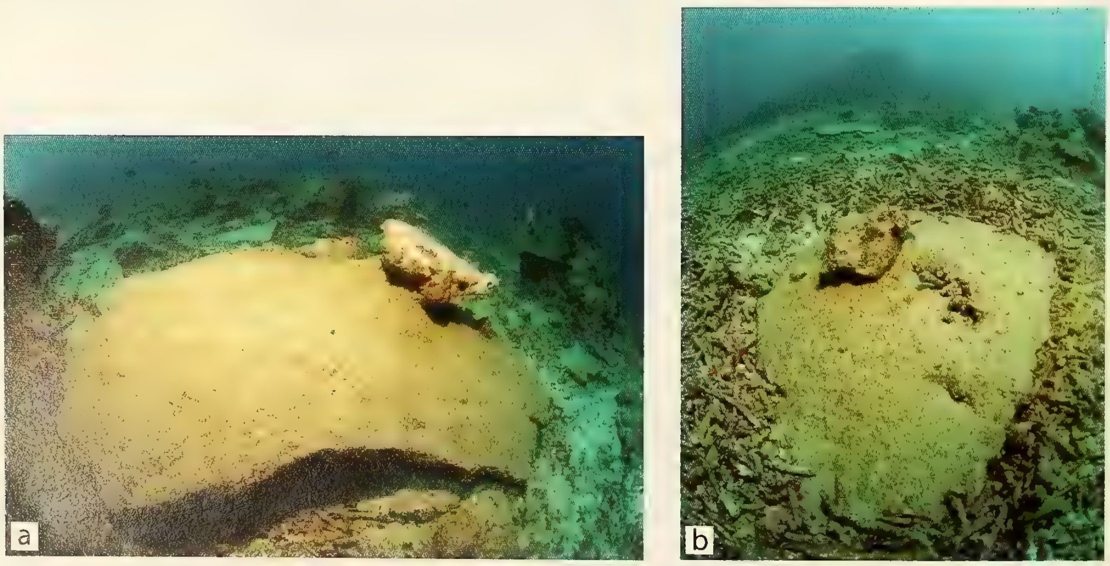

Figure 16. (a) Overturned dead *Acropora* spp. tables at 10 m water depth at Pulau Rondo, October 29, 2005. (b) overturned dead table coral surrounded by branching coral rubble.

Figure 17. Healthy reef communities at 10 m water depth at Pulau Rondo, October 29, 2005.

On the east side of Pulau Rondo the shallow survey was dominated by rock (50% cover) with rubble representing 30% of the substrate and live coral cover only 17%. The deep survey was dominated by rubble (70% cover), with little live coral cover (18%). Tsunami damage was observed in this area; specifically overturned dead *Acropora* spp. tables and a large tree trunk (over 6 m in length) had been deposited on the reef between 15 m and 18 m water depth (Fig. 18).

Figure 18. Tree trunk on reef at water depth of 18 m, Pulau Rondo, October 29, 2005.

At Pulau Bunta (Fig. 1, site 14), Manta Tows were conducted around the entire circumference of the island. The results suggested very high tsunami damage, with the reef being littered with small cylindrical branching coral fragments and a few overturned dead *Acropora* spp. tables being observed. Rock was estimated to account for 56% of the substrate observed and rubble 31%, with only 4% of the substrate being represented by live coral. Five coconut palm trunks were observed on the reef at depths of between 4 and 6 m. While conducting the Manta Tows, observations on the island confirmed that there had been significant tsunami impact here. Many coconut palms had fallen and much of the low-lying vegetation had been killed. Although this island is small (0.16 km x 0.38 km), approximately seven buildings were observed. Clearly these buildings were very new and piles of building debris were observed, indicating that the tsunami wave must have destroyed the buildings which previously stood there. Pulau Bunta would have been one of the first islands off the north coast of Aceh Province to be hit by the tsunami wave as it progressed northwards from the epicenter (Fig. 1).

DISCUSSION

Regional Reef Characteristics

Reefs of the Banyak region and northern islands displayed very similar benthic characteristics, with combined values of rock, hard coral and rubble contributing to between 85-90% of the overall benthos. Highest amounts of rubble were recorded in the northern islands, which may suggest that these offshore islands are exposed to a high energy environment due to oceanic swell generated thousands of kilometers away in the Indian Ocean (Tomascik et al., 1997). The reefs of the north coast of Aceh were typified by bare coral pavement with little rubble, and these reefs displayed a soft coral community that was not observed at any other site.

Evidence of boat anchor damage and dynamite fishing was observed at nearly all survey sites, suggesting that continuously high levels of anthropogenic stress on the reefs of Sumatra is having a more significant impact on coral reef health than that which resulted from the December 2004 tsunami.

Earthquake Damage

Earthquake damage resulted in three major alterations to the reef environment. Firstly, extensive mortality of reef-flat corals occurred due to uplift at Pulau Bangkaru. The corals that were uplifted and subsequently killed through subaerial exposure were those on the shallow reef-flat, and due to the naturally harsh nature of the reef-flat environment these corals would have been more resistant to natural environmental stress (e.g. higher water temperatures and solar radiation) than other corals further down the reef slope. Large (> 2 m diameter) microatolls, massive corals typically with a dead, flat upper surface surrounded by a living margin (Scoffin and Stoddart, 1978), were uplifted approximately 1.5 m above sea-level on the southwest coast of Simeulue island (Sieh, 2005) and smaller raised microatolls were observed at Pulau Bangkaru. As the upward growth of microatolls is constrained by sea level through prolonged exposure at low spring tides, microatolls act as natural recorders of sea level (Scoffin and Stoddart, 1978; Woodroffe and McLean, 1990; Zachariasen et al., 1999). In regional terms it has been suggested that a 1,000 km stretch of reef along the plate boundary from the Andaman and Nicobar islands to Sumatra has suffered uplift or submergence as a result of the December 2004 earthquake (Bilham, 2005). Consequently a huge number of reef-flat corals and microatolls have been killed in this region. There are few coral species that are common to both reef-flat areas and reef slope areas in this region, the most dominant being *Porites lutea* (Brown, 2005, pers. comm.; Phongsuwan and Brown, 2007), and the loss of so many other reef-flat coral species is likely to have serious implications for the re-population of the reefs of the region.

Secondly, reef uplift at Pulau Bangkaru has brought reef-front corals into the reef-flat zone. The corals that once thrived at deeper depths on the reef have now been uplifted to within a few meters of the surface and only time will tell how well these corals will survive after experiencing such a radical vertical shift in environments. Although

it is conceivable that these corals will adapt to their new, warmer water temperature and associated increased solar radiation, typically, such adaptations are only successful through gradual change over long time periods. However, it must also be considered that some species may be more able to adapt than others, which may alter the coral community composition.

Thirdly, moving further north, effects of the earthquake were observed at the islands of Pulau Baleh and Bagu, but unlike at Pulau Bangkaru where the reefs had been uplifted, these islands, and thus the surrounding reefs, had been submerged as a result of the earthquake. Although little structural damage was observed as a result of the tsunami on the reefs of these islands, the displacement of shallow reefs to deeper zones due to this tectonic plate shift may, over time, have implications for the reef ecosystem. Corals are extremely sensitive and very susceptible to variations in temperature. Consequently, a vertical shift of even as little as a meter could have severe consequences for the coral community.

Tsunami Damage

A wide spectrum of tsunami damage was observed over a large distance (650 km) in a short period of time. Typically, it was only possible to survey one or two sites at each island visited, yielding only a snap-shot of the overall reef environment. Therefore, generalisations of the degree of tsunami impact at different sites must be regarded with due caution.

No discernable tsunami damage was observed on the reefs of Pulau Karang or Pulau Bangkaru, the most southerly islands (Fig. 1, sites 2 and 3). It is possible that the reefs of these islands were sheltered from the tsunami wave by the large island of Simeulue, which lies 44 km south of the earthquake's epicenter (Fig. 1). Some tsunami damage was observed on the reefs of the northern offshore islands and on the north coast of Aceh Province. The most frequently observed damage was overturned *Acropora* spp. tables, overturned massive *Porites* spp. colonies and tree debris on the reef. Tsunami impact was exhibited as pockets of damage (although larger areas than displayed as a result of dynamite fishing) as opposed to huge areas of the reef being completely destroyed. Due to the limited amount of surveys undertaken, it is not possible to discuss variations in tsunami damage with respect to depth or aspect. For example, at some sites tsunami damage was observed on the deep transect but not on the shallow transect and vice versa, and it is not clear why this may have been the case.

The reef area observed to be most affected by the tsunami was on the north coast of Aceh, a site in the centre of a large bay between two headlands. Although due to the random and dispersed nature of the surveys it is difficult to make any comment on the pattern of tsunami damage, it could be suggested that here the tsunami waves may have been refracted off the headlands either side of the bay and compounded in the centre of the bay causing extensive damage at this central bay site. Similar results have been reported elsewhere, for example, more extensive tsunami induced reef damage was observed in bay areas of Sri Lanka (Rajasuriya, 2005).

CONCLUSIONS

In summary, 54% of the sites surveyed showed no tsunami damage, 31% showed low to moderate damage and 15% showed high levels of damage. Although minimal coral recruitment subsequent to the earthquake and tsunami was observed, typically the reefs of Sumatra displayed between 30% and 65% live coral cover (Fig. 2). Some of the overturned corals observed in Sumatra were still alive but others were dead. However, some of these dead corals were well eroded, suggesting that they may have been dead but still standing prior to the tsunami event. Dead standing corals are far more susceptible to tsunami damage due to their weak attachment onto the substrate. It follows logic that reefs which are already subjected to high anthropogenic stress are likely to suffer the most as a result of tsunami impact (Baird et al., 2005).

So, how long will it take the reefs of these Aceh islands to recover from the tsunami impact? When talking about reef recovery, it is important to look at the type of damage observed. Many of the overturned corals that were observed contained live tissue. Although it is unreasonable to assume that the portion of live coral now resting on the seabed will survive, the colony should gradually spread across the bare substrate which was once the base area. The surviving parts of these colonies will also be an important larval source for re-populating the reef. The recovery rates are expected to take significantly longer in those areas where corals were killed as a result of the tsunami. For example, at Pulau Rondo some overturned *Acropora* spp. tables were already dead (Fig. 16a and b) and the amount of branching coral rubble on the eastern side of the island suggested that there was considerable tsunami damage here. However, it is important to note than even in areas where severe tsunami damage was observed and corals were killed as a result of the event, there were still large areas of healthy coral present, which will serve to repopulate the damaged reef.

Post-tsunami reef studies in Thailand found that 66% of the 174 sites surveyed showed no or very little damage, with only 13% exhibiting severe damage (> 50% of colonies affected) (Brown, 2005; Phongsuwan and Brown, 2007). It has been suggested that these reefs will recover from the tsunami event within the next 5-10 years (Brown, 2005; Phongsuwan and Brown, 2007). The reefs of Sumatra appear to have suffered similar levels of damage from the December 2004 tsunami to that reported from the surveys in Thailand. It can therefore be reasonably suggested that recovery times will be similar for the reefs of Sumatra, that is, the reefs are likely to recover within approximately 5 years and full recovery of even severely damaged reefs will occur within the next decade.

ACKNOWLEDGEMENTS

The three organizations responsible for this survey are: The Khaled bin Sultan Living Oceans Foundation, Reef Check International and IUCN (World Conservation Union). Primary funding for this project was graciously provided by the Khaled bin Sultan Living Oceans Foundation. Our sincere gratitude goes to the Indonesian Government for granting permission for this research to be conducted.

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DISTURBANCE TO CORAL REEFS IN ACEH, NORTHERN SUMATRA: IMPACTS OF THE SUMATRA-ANDAMAN TSUNAMI AND PRE-TSUNAMI DEGRADATION

BY

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ABSTRACT

The Sumatra-Andaman tsunami of 26 December 2004 was the first to occur in areas for which good ecological data existed prior to the event and consequently provided a unique opportunity to assess the effects of this type of natural disturbance in tropical marine ecosystems. Less than 100 days after the event we visited 49 sites on coral reefs in northern Aceh, Indonesia, all within 300 km of the epicentre, to determine the nature and extent of tsunami damage and pre-tsunami disturbance. Reef fish diversity and abundance were also assessed in relation to tsunami impact and existing marine resource management regulations. At these sites, the initial damage to corals, while occasionally spectacular, was surprisingly limited and trivial when compared to pre-existing damage most probably caused by destructive fishing practices. The abundance of up-turned corals was highly dependent on habitat and largely restricted to corals growing in unconsolidated substrata at depth, a feature we believe unique to tsunami disturbance. Other evidence of tsunami damage, including the abundance of broken corals and recently killed corals was patchy and varied unpredictably between sites: reef aspect, geographic location and management regime had no significant effect on these variables with the exception of broken live corals which were more abundant at locations where the tsunami was larger. Interestingly, there was little correlation between damage variables, suggesting the type of damage observed was strongly influenced by which corals were present at a particular site or depth. In contrast, reef condition was clearly correlated with the management regime. Coral cover was on average 2-3 times higher on reefs managed under the traditional Acehnese system, Panglima Laut, and in the Pulau Rubiah Marine Park when compared to open access areas. Turf algae and coral rubble were 2-3 times

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more abundant in open access sites compared with managed areas. These results are consistent with a history of destructive fishing practices, such as bombing and cyanide fishing in open access areas. Coral reef fish abundance and diversity did not differ among management zones, despite the fact that Pulau Rubiah Marine Park has been closed to fishing for 10 years. However, there were consistent differences in the structure of the reef fish assemblages among these zones. For example, the near absence of chaetodontids at open access sites is probably the result of low coral cover. The high abundance of scarids and acanthurids in the Marine Park, suggests that while management efforts have failed to allow fish to increase in abundance, they have been effective at protecting certain species. The tsunami had no detectable affect on reef fish assemblages at these sites. This lack of major damage means that neither the conservation priorities nor the risks to reefs have been changed by the tsunami and it is vitally important that resources are not directed to short term, small scale, rehabilitation programs which will not reverse long term declines in reef condition which were evident at many of our sites.

INTRODUCTION

Disturbance has a significant role in determining the structure and dynamics of ecological communities (Pickett and White, 1985; Petraitis et al., 1989), especially in coastal marine habitats, which appear particularly susceptible to a wide range of natural and anthropogenic disturbances (e.g., Alongi, 2002; Hughes et al., 2003). These disturbances, including severe tropical storms, temperature fluctuations, terrestrial run-off, and diseases, vary in their scale, intensity and frequency (Hughes and Connell 1999), contributing to extreme spatial and temporal variability in the biological structure of shallow-water marine communities (Karlson and Hurd, 1993). There is increasing evidence, however, that effects of natural disturbances are being further compounded by anthropogenic stresses leading to directional changes in the structure of marine habitats. In the extreme, synergistic effects of multiple chronic disturbances lead to irreversible and fundamental shifts in biological structure. On coral reefs, chronic over-fishing combined with excess nutrients has led to permanent shifts from coral-dominated to algal-dominated benthos (Done, 1992; Hughes, 1994; McCook, 1999). This in turn may have significant repercussions for the long-term survival of coral associated reef fishes (reviewed by Wilson et al., 2006).

Coastal marine habitats in Indonesia have been subject to a long-history of disturbance from destructive fishing practices (Edinger et al., 1998) combined with severe episodes of sedimentation and increased turbidity associated with monsoonal rains and land based runoff (McManus, 1988; Hopley and Suharsono, 2002). On December 26th, 2004, these habitats were further subject to an extreme punctuated disturbance in the form of the Sumatra-Andaman earthquake and subsequent tsunami. The spatial scale and magnitude of this tsunami has no historical precedent and many aspects of the event, such as the length of the fault line and the speed of the slip suggested it was almost unique (Lay et al., 2005, Vigny et al. 2005). Estimates of the return time for tsunamis greater than 10 m wave height are 1000 years for the Indian Ocean (Tsunami Risks Project,

2005) indicating that this was indeed a rare natural disturbance. While smaller tsunamis are relatively common, for example since 1883, 35 tsunamis have occurred in Indonesia alone (Birowo et al., 1983), there are as yet few quantitative studies of the damage they cause to coral reef communities (Tomascik, 1997a, 572-4) and consequently the event provided a unique opportunity to assess the effects of this type of natural disturbance in tropical marine ecosystems.

Initial reports of damage to coral reefs following the tsunami suggested that greatest impacts were in Indonesia and the Andaman Islands (UNEP, 2005). In Indonesia, initial assessments based on satellite imagery suggested that 97,250 ha of coral reef habitat was affected with a potential loss of 3061 ha valued at $332 million dollars (Anon, 2005). Region reports have since revealed that tsunami damage varied widely, and often unpredictably. For example, Baird et al. (2005) described the damage as occasionally spectacular, but surprisingly limited, given the proximity of their sites in Aceh to the epicentre of the December 26, 2004 earthquake. Damage to the reefs of Thailand (Comley et al., 2005; Phongsuwan and Brown, 2007) and the Maldives (Gunn et al., 2005) was similarly patchy, but generally low. In contrast, widespread damage was reported to reef habitats in the Andaman and Nicobar islands (Kulkarni, 2001), Sri Lanka (CORDIO, 2005a; Meynell and Rust, 2005) and even the Seychelles (Obura and Abdulla, 2005), which is perhaps surprising given the distance from the epicenter of the earthquake. The only study to present data from both before and after the tsunami detected no change to shallow coral assemblages on Pulau Weh in Aceh (Baird et al., 2005), despite an estimated run-up height of 5 m at this location (USGS, 2005).

In this study we assessed the condition of coral reefs in northern Aceh region of Sumatra to determine the effect of the Sumatra-Andaman earthquake and tsunami on coral reef communities. The status of coral reef communities (both coral and fish communities) was examined against a background of considerable prior disturbance. Most importantly, reefs in northern Aceh have been subject to destructive fishing practices, such as cyanide fishing and bombing, which have devastating effects on fish stocks as well as the benthic reef habitats. Accordingly, we sampled sites under 3 different management regimes; open access areas, Pulau Rubiah Marine Reserve, and the tradition Acehnese management practice, Panglima Laut.

METHODS

In April 2005 (<100 days after the tsunami) we visited 49 sites in northern Aceh located within 300 km of the epicentre of the earthquake (Fig. 1). Study sites were located within three different management regimes; 1) a central government managed marine tourism reserve centered around Pulau Rubiah, which we will call Kawasan Wisata, 2) community based traditional Acehnese marine management system known as Panglima Laut, and 3) open access areas. To document current reef condition and assess potential tsunami damage we used the rapid assessment techniques recommended by the World Conservation Monitoring Centre (CORDIO, 2005b). Reef fish abundance and diversity were also assessed a subset of these sites.

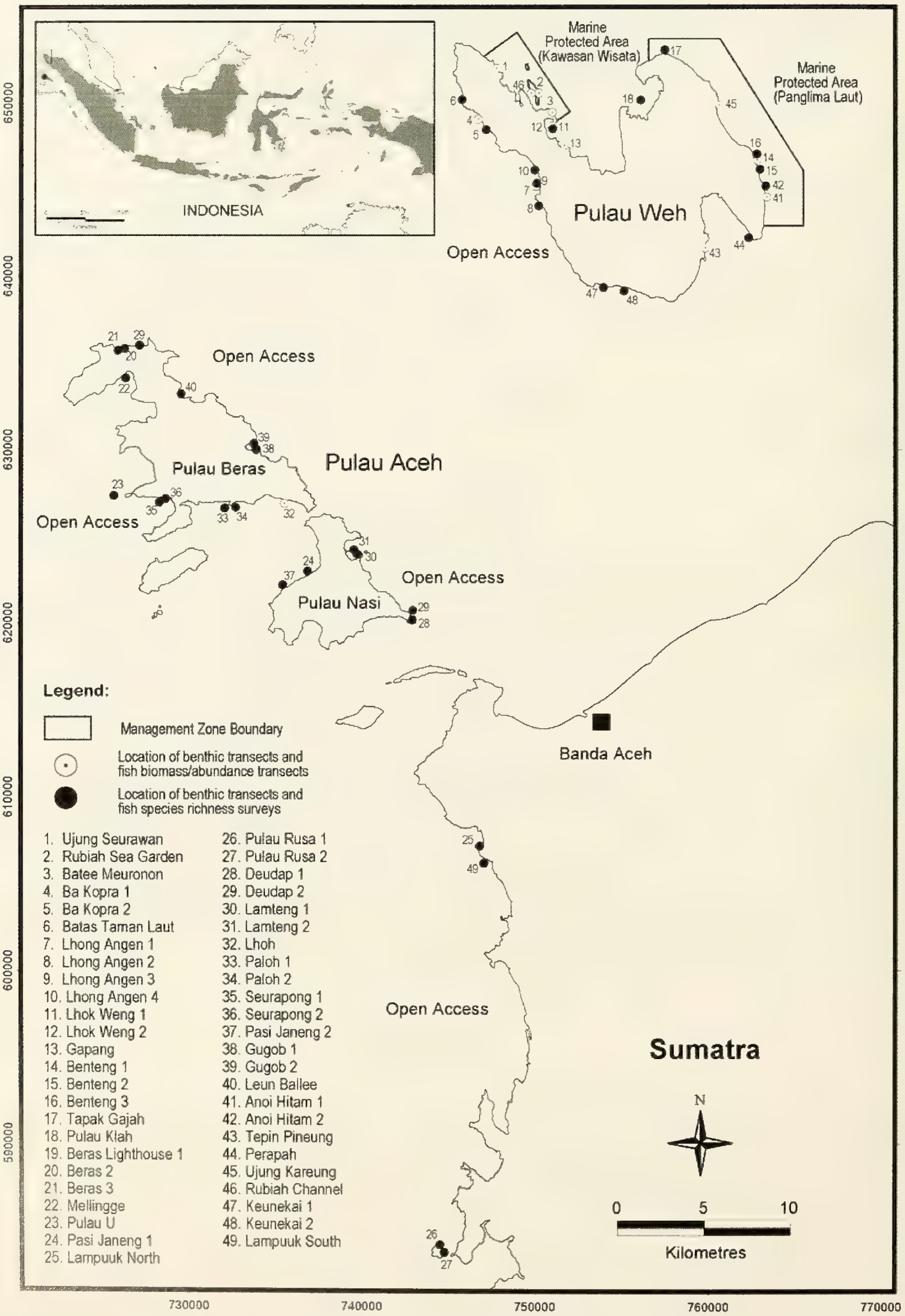


Figure 1. Location of sites for assessment of coral reef substrate variables (47 sites) and coral reef fish (31 sites), northern Aceh, Indonesia.

Surveys were conducted at 47 of the 49 sites to assess the biological and physical structure of the reef benthos, and also to quantify recent physical damage attributable to the tsunami (Fig. 1). At each site 16-32 replicate 10 x 1 m belt transects were conducted on the reef crest (0-2 m) and/or the reef slope (3-10 m). On these transects the percentage cover of the following variables was recorded, three describing reef condition: 1) live coral cover, 2) coral rubble, and 3) turf algae; and three indicative of recent reef damage: 1) coral colonies that were up-turned or displaced (Fig. 2E), 2) attached colonies with partial mortality or broken branches (Fig. 2F), 3) recently killed colonies (Fig. 2B). The following categories were recorded as estimates of cover following CORDIO (2005b): 0% = 0; 1-10% = 5; 11-30% = 20; 21-50% = 30; 51-75% = 62.5; 76-100% = 87.5). For statistical analysis, the mid-point of each category was used to calculate mean values for each group.

To assess potential impacts of the tsunami on reef associated fauna, species diversity of reef fish assemblages was quantified during 20 min timed swims at 31 sites. Two divers (SP, TK) swam along a pre-designated path recording all species observed and the lists combined to provide an estimate of species richness for each site. Surveys were conducted along a zig-zag path starting at ~25 m depth and extending to the reef crest. The total area surveyed was approximately 300 m x 100 m per site.

The abundance of fishes within each of 45 major reef fish families was documented at 13 sites: 3 located within Kawasan Wisata where all fishing is prohibited; 3 within Panglima Laut where only artisanal line fishing is permitted; the remaining 7 sites were located in open use areas, where fishing activities are largely unregulated, and includes line-fishing, muro-ami (a particularly destructive form of netting), netting, trapping, and spear fishing. The size and number of all fishes within each of 45 families were recorded simultaneously using 3 replicate 50 m transects on the reef crest (<2 m). Transects were run parallel to the reef crest and spaced >5 m apart. The transect line was delineated using a 50 m fibreglass tape, along which small fishes (<10 cm TL) were surveyed in a 2m wide path and larger fishes (>10 cm TL) were surveyed in a 5 m wide path.

The different regimes under which sites were managed should influence reef condition. Consequently, we tested for significant difference in mean cover of coral, filamentous algae and coral rubble among management zones using a 2-way ANOVA. Factors in the model were management (fixed; 3 levels, as described above) and site nested with management (random; 4 to 28 sites per management regime). For these variables the analysis was repeated twice; once for shallow sites ($n = 38$), and again for deep sites ($n = 45$) because at many sites transects were only run at one depth.

Tsunami run-up, which was evident throughout the region as a prominent scar from which vegetation had been stripped, was higher in Pulau Aceh and the mainland when compared to Pulau Weh. Measurements by the United States Geological Survey (USGS) confirmed these observations, recording maximum run-up heights in Pulau Aceh and the mainland as 22 m and 26 m respectively, 4 to 5 times higher than on Pulau Weh (~5m) (USGS, 2005). In addition, our initial observations (see Baird et al., 2005) suggested that damage was habitat specific, in particular, up-turned corals appeared to be more abundant at depth (> 2 m) than in the shallows (< 2 m). Consequently, we used a 3 way-ANOVA to test for mean differences in the proportion of the 3 damage variables (up-turned coral, broken coral, recently killed coral) among locations, sites and between


A
B
C
D
E
F
G
H

depths. Factors in the model were location (fixed; 2 levels, Pulau Aceh/mainland, Pulau Weh), site nested within location (random; 17 and 24 levels) and depth (fixed: 2 levels, shallow and deep) which was crossed with both location and site nested within location. Only up-turned coral differed significantly between depths, so to increase the quantity of data for the other variables we ran a 2-way ANOVA as described above for the reef condition variable using transects from each depth.

Much work on tsunami damage to coastlines indicates that the angle of incidence between the tsunami and the coastline can influence the degree of damage, and shorelines fronting the tsunami would be expected to suffer greater damage than shorelines in the lee of the tsunami. Consequently, we used a 2-way ANOVA to test for differences in the mean proportion of up-turned coral, broken and recently killed coral among sites facing north, south, east and west. Factors in the model were reef aspect (fixed; 4 levels, north, south, east, and west facing reefs), and site nested within reef aspect (random; 3 to 19 site per aspect). Once again, to increase the data available for analysis shallow and deep transects were analysed separately. All damage and reef condition variables were arcsine transformed and the normality and homoscedasticity of the transformed data examined with graphical analyses of the residuals. Analyses were completed using SYSTAT v10.2.

Corals reef fish may also be influenced by different fishing restrictions enforced within management zones. Consequently, we tested for significant difference in mean abundance of coral reef fish among management zones using a 2-way ANOVA. Factors in the model were management (fixed; 3 levels, as described above) and site nested with management (random; 3 to 6 sites per management zone). Only a single estimate of diversity was made at each of 31 sites. Consequently, 1-way ANOVA was used to test for differences in mean species richness among management zones (fixed; 3 levels) with site values providing the replication within management. Both variables were $\log_e (x+1)$ transformed to improve homogeneity and normality, and analyses were completed using SYSTAT v10.2.

To explore spatial variation in the composition of reef fish assemblages, MANOVA was used to test for variation in the relative abundance of five major families (Acanthuridae, Chaetodontidae, Labridae, Scaridae, Serranidae and Pomacentridae) among 13 sites for which these data were available. All data were $\log_e$ transformed prior to analyses to improve homogeneity and normality, and analyses were completed using SPSS v11.0.

◀ **Figure 2.** **A.** Healthy colony of *Acropora muricata* in 1 m at site 49, November 2000. **B.** The same colony as in Fig 2A in April 2005. Despite an estimated wave height of over 12 m, the colony is still intact, however, the tissue has been smothered by sediment stirred up by the tsunami. **C.** Healthy reef in the shallows of Pulau Rubiah Marine Park site 46 in April 2005. **D.** A collapsed colony of *Heliopora* sp. Site 11 **E.** A buried *Porites* colony in approximately 3 m depth. Interestingly, this colony was less than 20m from the healthy reef in Fig. 2C, demonstrating the different impact of the tsunami on corals firmly attached to reef or rock when compared to corals growing in sand or rubble. **F.** Broken branches in an *Acropora* sp. site 26 in 0.5 m depth. The wounds have healed, however, the polyps have yet to begin growing again, suggesting the injury is recent, and most probably cause by debris mobilized by the tsunami. **G.** A large *Porites* colony, approximately 3 m diameter lies buried on the beach on Pulau Beras, site 36. **H.** A bleached Favites colony at site 27. The turbidity at some sites, in particular on the mainland and in Pulau Aceh, was very high, and continues to pose a threat to coral assemblages.

RESULTS

At these sites on the north and west coast of Aceh, where the tsunami was most ferocious, the initial damage to coral reefs, while occasionally spectacular (Fig. 2G), was surprisingly limited. Furthermore, damage was very patchy with often pronounced difference between adjacent sites. Tsunami damage was largely unpredictable: neither reef aspect, geographic location (a proxy for tsunami intensity) nor management zone had a significant effect on the amount of damage. The only clear patterns were a higher proportion of up-turned corals at depth and a higher proportion of broken corals on reef crests at Pulau Aceh and mainland sites. Reef condition, however, varied widely within the region and was clearly correlated with management regimes. Coral cover was high, and the cover of algae and rubble low at Kawasan Wisata and Panglima Laut sites. In contrast, coral cover was low and the cover of algae and rubble was high at open access sites.

The mean proportion of overturned corals was significantly higher at depth (shallow sites: 3.3 ± 0.35; deep sites; 7.6 ± 0.43; $F_{1, 33} = 9.4$, $P = 0.004$). This pattern was evident at most sites, except where the damage was low, such as most Panglima Laut sites (Fig. 3A), and at these sites, not surprisingly, there was no difference in the mean proportion of up-turned coral between depths, causing an interaction between depth and site (management) ($F_{33, 1464} = 4.1$, $P < 0.001$). While there was considerable variation among sites (management), the mean proportion of overturned corals did not differ among management zones ($F_{2, 33} = 0.500$, $P = 0.611$). All management regimes had some sites with moderate abundance of overturned coral and some sites with no overturned corals (Fig. 3A). Neither reef orientation, nor geographic location had any significant effect on the abundance of up-turned corals on either the reef crest or reef slope.

The mean proportion of broken live coral was significantly higher in the shallows at Pulau Aceh and mainland areas (21.6 ±1.65SE) compared with Pulau Weh (5.7 ±0.72SE) ($F_{1, 34} = 6.565$, $P = 0.0145$) (Fig. 3B) but this pattern was not repeated at depth ($F_{3, 41} = 2.3$, $P = 0.09$). The abundance of broken live coral was not significantly affected by management, depth, orientation, or geographic location on either the reef slope, or the reef crest. The abundance of recently killed corals was similarly unpredictable, with a few sites within each location experiencing high mortality, but at most sites no recently killed corals where recorded (Fig. 3C).

Damage variables were poorly correlated. Transects with a high proportion up-turned corals did not, generally, have a high proportion of broken coral ($r^2 = 0.087$), or recently killed coral ($r^2 = 0.003$). While there was weak correlation between broken coral and recently killed coral, only 15 % of the variation was explained by the relationship.

All measures of reef condition (i.e. live coral cover, turf algae, coral rubble) varied among management zones. Coral cover was significantly higher in the shallows at Kawasan Wisata (31.7±2.8) and Panglima Laut (52.2 ± 2.2 SE) sites when compared with open access sites (19.3±0.9) ($F_{2, 35} = 8.4$, $P < 0.001$) (Fig. 4A). This pattern was even more pronounced at depth where coral cover at Panglima Laut (44.8 ± 2.7 SE) and Kawasan Wisata (25.8±1.5SE) sites was 3 to 10 times higher than at open access zones (3.8±0.5) ($F_{2, 42} = 5.4$, $P < 0.008$). In contrast, to this pattern both turf algae ($F_{2, 35} = 8.4$, $P < 0.019$; Fig. 4B) and rubble ($F_{2, 35} = 3.7$, $P < 0.035$; Fig. 4C) were 10 – 20 times higher

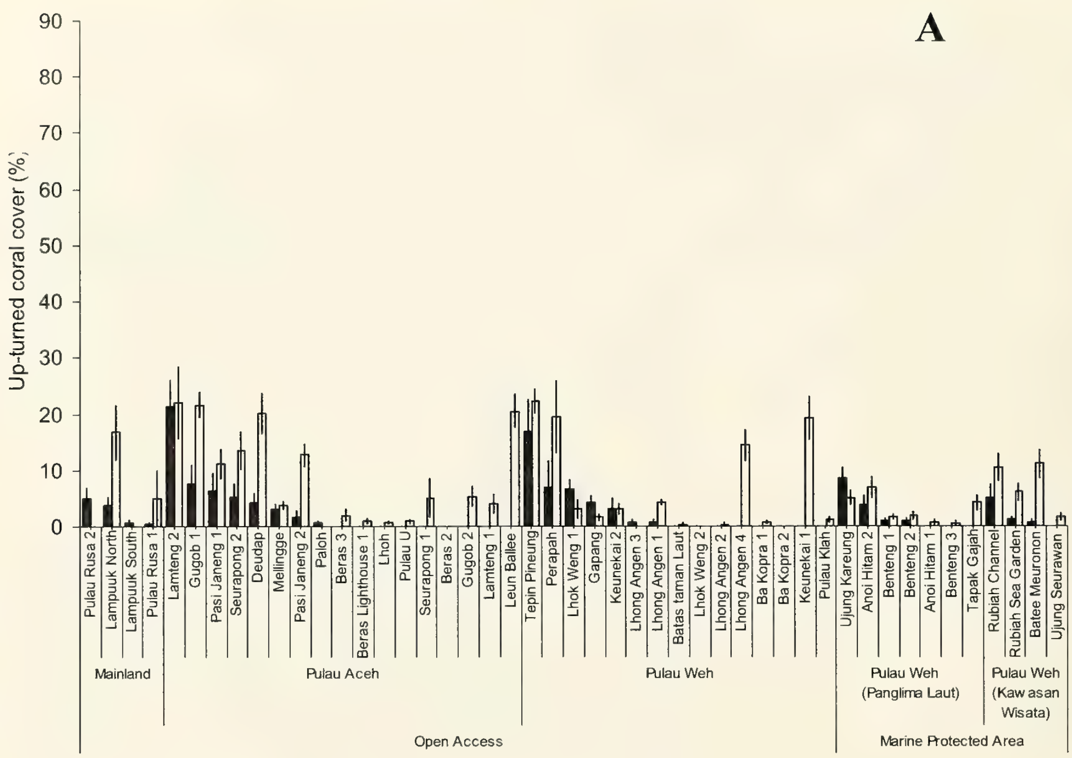
at open access sites (algae = 33.9 ± 1.4 SE; rubble = 20.4 ± 1.2 SE) when compared to Panglima Laut (algae =17.7 ± 2.4 SE; rubble = 1.5 ± 0.5SE) and Kawasan Wisata sites (algae = 3 ± 0.9 SE; rubble = 0.4 ±0.2 SE).

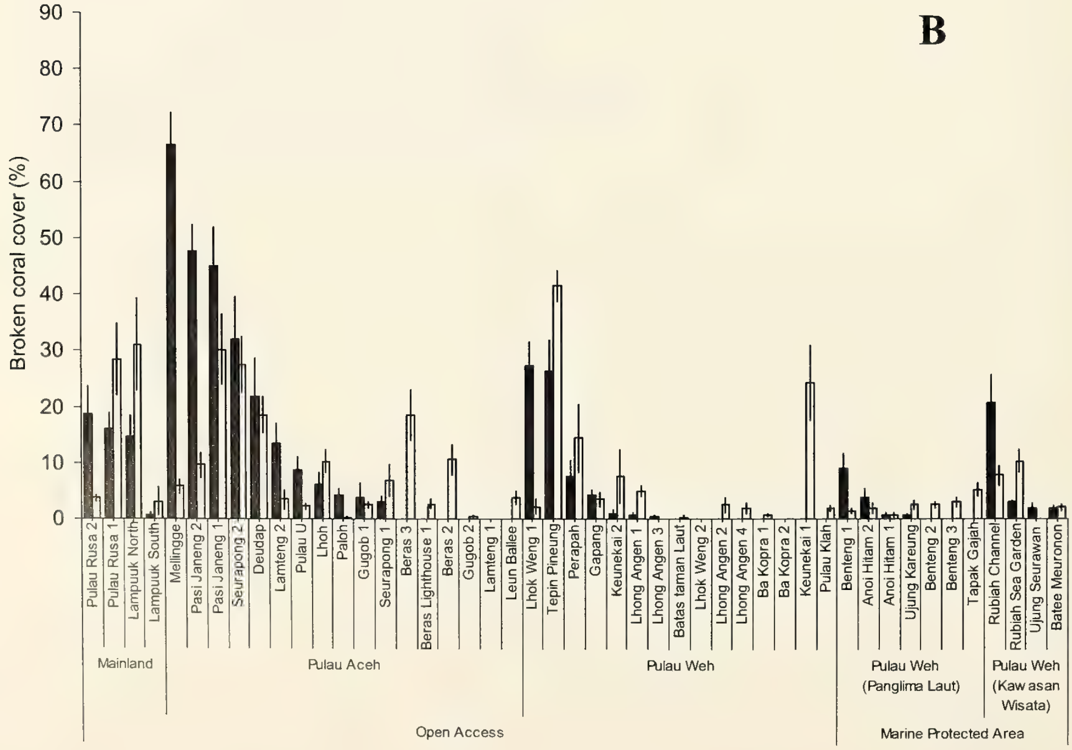
While the direct effects of the tsunami on the function of coral reef ecosystems were relatively minor, changes in the sediment regime following the tsunami have caused localized mortality and continue to threaten some reefs. For example, a previously flourishing *Acropora* assemblage at the southern edge of the fringing reef at Lampuuk (site 49, Fig. 1) was smothered by sediments causing complete mortality (Fig. 2B) compared with previous surveys in March 2003 (Fig. 2A). While these dead colonies were still intact in April 2005, by December 2005 they had completely disappeared. Other examples of indirect effects from the tsunami include bleached *Acropora* and faviid colonies (Fig. 2H) at sites 25, 27 and 28.

A total of 358 species of reef fishes were recorded across all 28 study sites surveyed during this study. The most speciose families were the Pomacentridae (59 species), Labridae (47 species), Chaetodontidae (32 species), Acanthuridae (28 species) and Scaridae (24 species). Species richness of reef fishes varied greatly among sample sites, ranging from 14 species at Pulau Rusa 2 (site 27, Fig. 1) to 103 species at Gugob 1 (site 38) on the north-east side of Palau Beras (Fig. 5). The species richness of coral reef fishes varied greatly even among closely positioned sites. For example, 73 species of reef fishes were recorded at Paloh (site 33) on the southern side of Palau Beras, whereas only 19 species were recorded at Lhoh (site 32), located <5 km away. Mean species richness did not vary among management zones and ranged from 36.00 ± 3.46SE at Panglima Laut sites to 48.7 ± 5.47SE at open access sites ($F_{2, 28} = 0.45$, $P = 0.645$).

The mean abundance of reef fishes (averaged across all families) varied by an order of magnitude among sites, ranging from 4900 (± 167.73SE) fishes per hectare at Anoi Hitam 1 (site 41), up to 94,968 (± 68,695SE) fishes per hectare at Rubiah Channel (site 46) (Fig. 6). The overall abundance of fishes varied greatly among sites ($df_{2, 10}$, $F = 4.32$, $P < 0.05$), but there was no significant variation attributable to differences in management ($df_{2, 10}$, $F = 0.36$, $P > 0.05$). The most abundant family of fishes was the Pomacentridae, which accounted for more than 55.9% of all fishes counted. The next most abundant families of fishes were the Acanthuridae, Serranidae and Chaetodontidae, although families comprising mostly small or cryptic fishes (e.g., Apogonidae or Blennidae), which comprise a significant component of the ichthyofauna on coral reefs (Munday and Jones 1998) were not surveyed.

While there was little difference in either the abundance or diversity of fishes among management zones, the structure of coral reef fish assemblages did vary significantly among both management zones (MANOVA, Pillia's Trace = 1.04, $F_{14,42} = 3.25$, $P = 0.002$) and sites within each management zone (MANOVA, Pillia's Trace = 3.10, $F_{70,182} = 2.06$, $P < 0.001$). The structure of coral reef fish assemblages at sites within the Kawasan Wisata was fairly distinctive, characterized by high abundance of Acanthuridae (Fig. 7). Similarly, the three sites from the Panglima Laut all had very similar fish assemblages, with much higher abundance of Labridae compared to the Kawasan Wisata (Fig. 7). Notably, fishes from the families Acanthuridae, Labridae Chaetodontidae, and Serranidae all tended to be more abundant at Kawasan Wisata and Panglima Laut sites compared to open access areas (Fig. 7). Variation among sites within


A
Up-turned coral cover (%)
90
80
70
60
50
40
30
20
10
0
Pulau Rusa 2
Lampuuk North
Lampuuk South
Pulau Rusa 1
Lamteng 2
Gugob 1
Pasi Janeng 1
Seurapong 2
Deudap
Mellingge
Pasi Janeng 2
Paloh
Beras 3
Beras Lighthouse 1
Lhoh
Pulau U
Seurapong 1
Beras 2
Gugob 2
Lamteng 1
Leun Ballee
Tepin Pineung
Perapah
Lhok Weng 1
Gapang
Keunekai 2
Lhong Angen 3
Lhong Angen 1
Batas taman Laut
Lhok Weng 2
Lhong Angen 2
Lhong Angen 4
Ba Kopra 1
Ba Kopra 2
Keunekai 1
Pulau Klah
Ujung Kareung
Anoi Hitam 2
Benteng 1
Benteng 2
Anoi Hitam 1
Benteng 3
Tapak Gajah
Rubiah Channel
Rubiah Sea Garden
Batee Meuronon
Ujung Seurawan
Mainland
Pulau Aceh
Pulau Weh
Pulau Weh (Panglima Laut)
Pulau Weh (Kaw asan Wisata)
Open Access
Marine Protected Area


B
Broken coral cover (%)
90
80
70
60
50
40
30
20
10
0
Pulau Rusa 2
Pulau Rusa 1
Lampuuk North
Lampuuk South
Mellingge
Pasi Janeng 2
Pasi Janeng 1
Seurapong 2
Deudap
Lamteng 2
Pulau U
Lhoh
Paloh
Gugob 1
Seurapong 1
Beras 3
Beras Lighthouse 1
Beras 2
Gugob 2
Lamteng 1
Leun Ballee
Lhok Weng 1
Tepin Pineung
Perapah
Gapang
Keunekai 2
Lhong Angen 1
Lhong Angen 3
Batas taman Laut
Lhok Weng 2
Lhong Angen 2
Lhong Angen 4
Ba Kopra 1
Ba Kopra 2
Keunekai 1
Pulau Klah
Benteng 1
Anoi Hitam 2
Anoi Hitam 1
Ujung Kareung
Benteng 2
Benteng 3
Tapak Gajah
Rubiah Channel
Rubiah Sea Garden
Ujung Seurawan
Batee Meuronon
Mainland
Pulau Aceh
Pulau Weh
Pulau Weh (Panglima Laut)
Pulau Weh (Kaw asan Wisata)
Open Access
Marine Protected Area

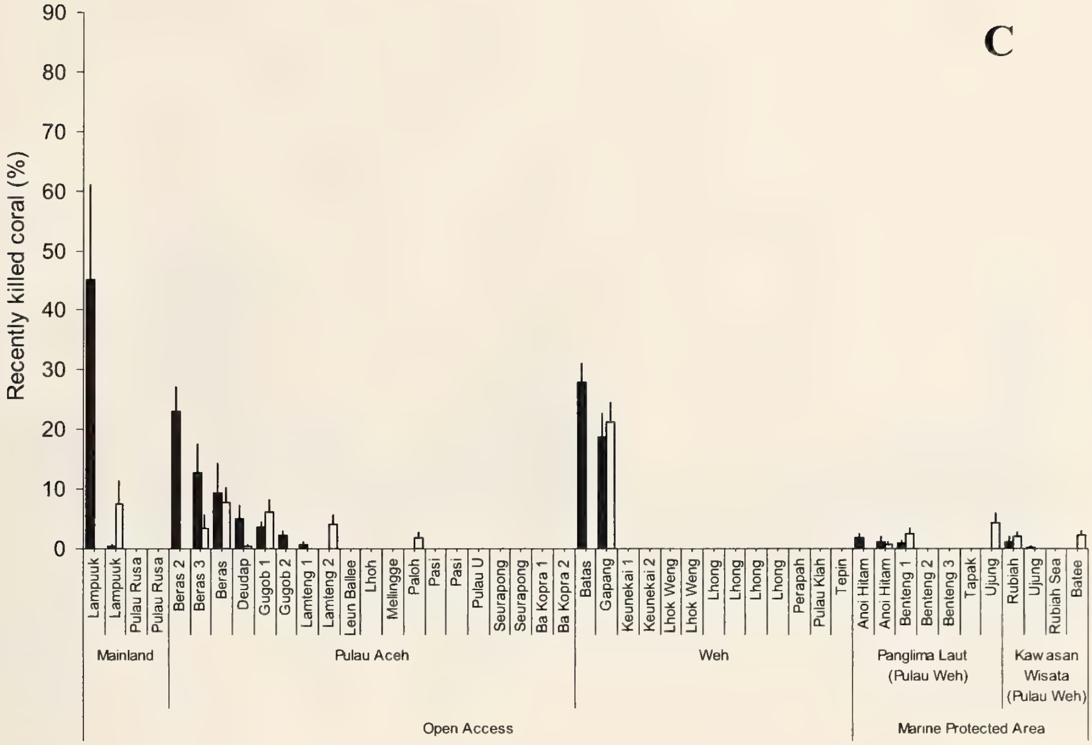
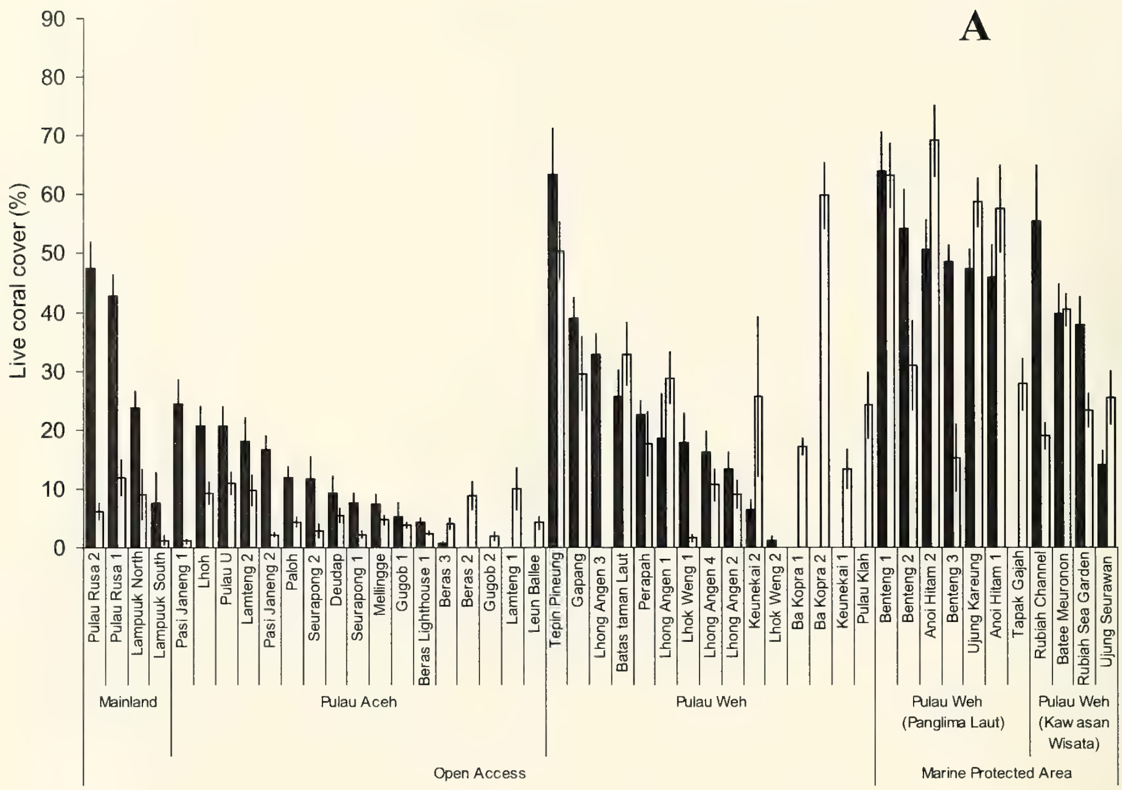


Figure 3. Spatial and habitat variation in damage variables at 47 sites in northern Aceh. Values are the mean + one standard error. Black bars represent transects run in the shallows (<2 m) and white bars represent transects run at depth (>2 m). A. Up-turned coral. B. Broken live coral. C Recently killed coral.


A
Live coral cover (%)
90
80
70
60
50
40
30
20
10
0
Pulau Rusa 2
Pulau Rusa 1
Lampuuk North
Lampuuk South
Pasi Janeng 1
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Seurapong 1
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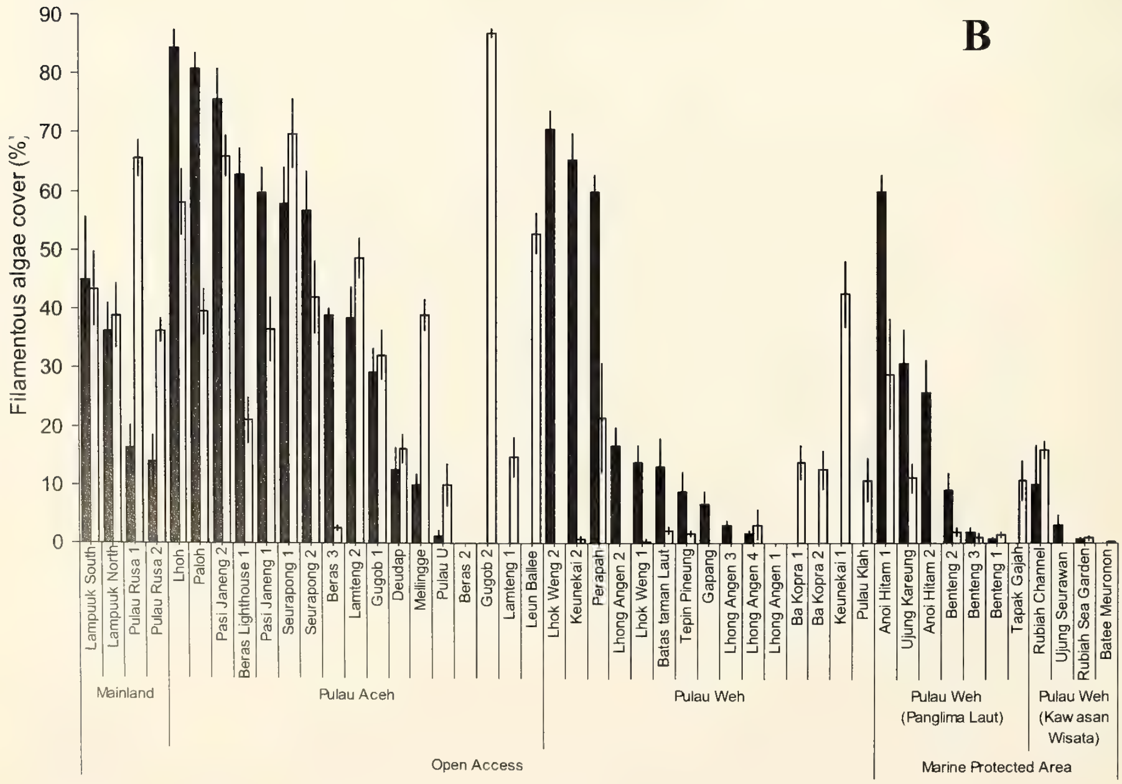
Tepin Pineung
Gapang
Lhong Angen 3
Batas taman Laut
Perapah
Lhong Angen 1
Lhok Weng 1
Lhong Angen 4
Lhong Angen 2
Keunekai 2
Lhok Weng 2
Ba Kopra 1
Ba Kopra 2
Keunekai 1
Pulau Klah
Benteng 1
Benteng 2
Anoi Hitam 2
Benteng 3
Ujung Kareung
Anoi Hitam 1
Tapak Gajah
Rubiah Channel
Batee Meuronon
Rubiah Sea Garden
Ujung Seurawan
Mainland
Pulau Aceh
Pulau Weh
Pulau Weh (Panglima Laut)
Pulau Weh (Kaw asan Wisata)
Open Access
Marine Protected Area


B
Filamentous algae cover (%)
90
80
70
60
50
40
30
20
10
0
Lampuuk South
Lampuuk North
Pulau Rusa 1
Pulau Rusa 2
Lhoh
Paloh
Pasi Janeng 2
Beras Lighthouse 1
Pasi Janeng 1
Seurapong 1
Seurapong 2
Beras 3
Lamteng 2
Gugob 1
Deudap
Mellingge
Pulau U
Beras 2
Gugob 2
Lamteng 1
Leun Ballee
Lhok Weng 2
Keunekai 2
Perapah
Lhong Angen 2
Lhok Weng 1
Batas taman Laut
Tepin Pineung
Gapang
Lhong Angen 3
Lhong Angen 4
Lhong Angen 1
Ba Kopra 1
Ba Kopra 2
Keunekai 1
Pulau Klah
Anoi Hitam 1
Ujung Kareung
Anoi Hitam 2
Benteng 2
Benteng 3
Benteng 1
Tapak Gajah
Rubiah Channel
Ujung Seurawan
Rubiah Sea Garden
Batee Meuronon
Mainland
Pulau Aceh
Pulau Weh
Pulau Weh (Panglima Laut)
Pulau Weh (Kaw asan Wisata)
Open Access
Marine Protected Area

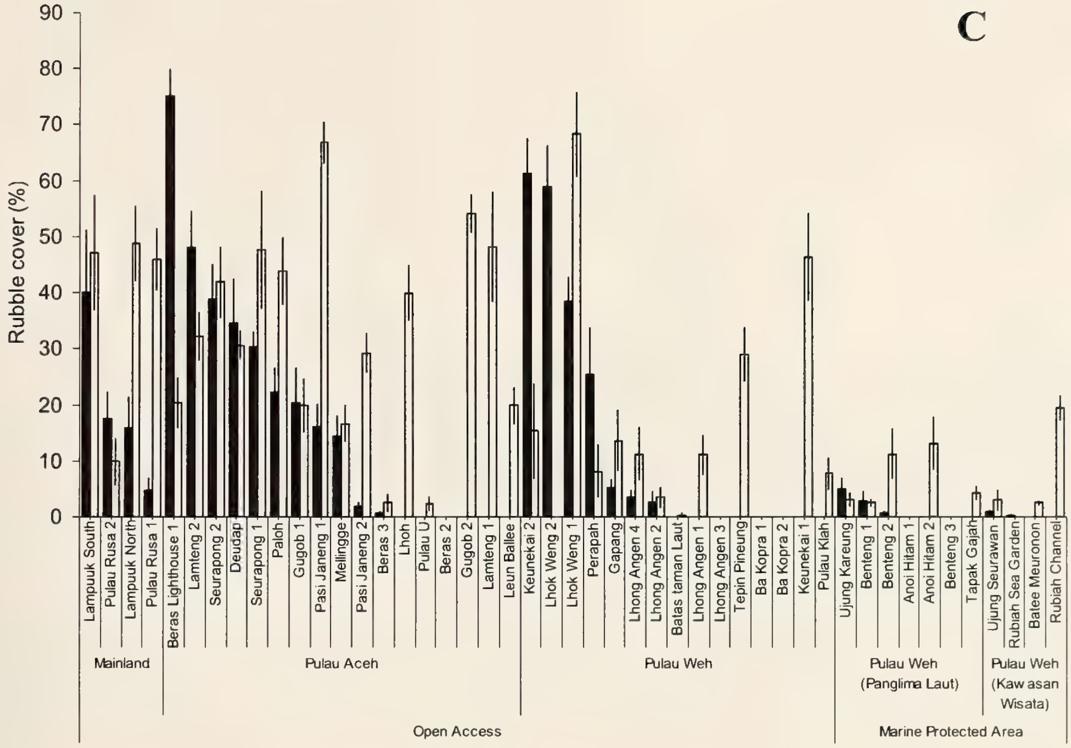


Figure 4. Spatial and habitat variation in reef condition variables at 47 sites in northern Aceh. Values are the mean + one standard error. Black bars represent transects run in the shallows (<2 m) and white bars represent transects run at depth (>2 m). A. Live coral. B. Filamentous algae. C. Rubble.

each management regime was highest among open access sites, which did not appear to be grouped by geographic proximity. For example, Lhok Weng 1 (site 11) and Gapang (site 13), which are open access sites located within 1 km of each other on the northern side of Pulau Weh, had very different fish assemblages (Fig. 7). The fish assemblage at Gapang, and also Batee Meuronon (site 3), were most similar to those of sites within the Panglima Laut, with high abundance of Labridae, Chaetodontidae and Serranidae, whereas these families of fishes were rare at most open access areas, especially Lhok Weng 1 (site 11) and Tepin Pineung (site 43) (Fig. 7).

DISCUSSION

Our detailed, large scale and quantitative survey of the reefs in northern Aceh clearly demonstrates that the first reports of tsunami damage from this region were grossly exaggerated. The value of such qualitative assessments must be questioned, they are all too easy to make, and because they are typically the first available news, they capture undue attention. Furthermore, the uncritical repetition of these studies (e.g., Tun et al. 2005) must also be questioned, because it only serves to perpetuated the myth, and obscure its provenance. The overwhelming picture from the majority of reports from the Indian Ocean (Baird et al., 2005; Brown, 2005; Phongsuwan and Brown, 2007; Comley et al., 2005; Gunn et al., 2005) is that the damage caused to coral reefs by the Dec 26 earthquake and tsunami was rarely of ecological significance, and at our sites in northern Aceh, tsunami damage was trivial when compared with that caused from chronic human misuse.

Few clear patterns were evident in the tsunami damage observed: neither reef aspect, geographic location (i.e. tsunami intensity) nor management zone (i.e. reef quality) significantly affected any of the damage variables, with the one exception being high abundance of broken live coral on mainland and Pulau Weh reef crests. This is perhaps surprising, and contrasts with results reported elsewhere (Baird et al., 2005; Brown, 2005; Chatenoux and Peduzzi, 2005). However, tsunamis interact with submarine and coastal topography in complex ways and interference, resonance, and reflection can concentrate the force of the tsunami in unexpected locations, such as the lee of islands, small embayments and channels (Tsunami Risks Project, 2005). The earthquake of 26 December 2004 generated a tsunami in Aceh which consisted of at least 3 main waves (a wave train), preceded by an initial draw down (Lay et al., 2005). The first wave was estimated at 12 m by eyewitnesses before it broke on the reefs on the Acehnese coast. The second wave was considerably larger, with flow heights at the coast ranging from 10.0 to 15.0 m (Borrero 2005). Indeed, the northern tip of Aceh and the islands to the north were in effect hit by two wave trains, one from the north and one from the west (Borrero 2005). With such a complex tsunami event up such a large scale in an area with many islands of contrasting geography untangling the features that made one reef more susceptible to damage than another is possibly intractable.

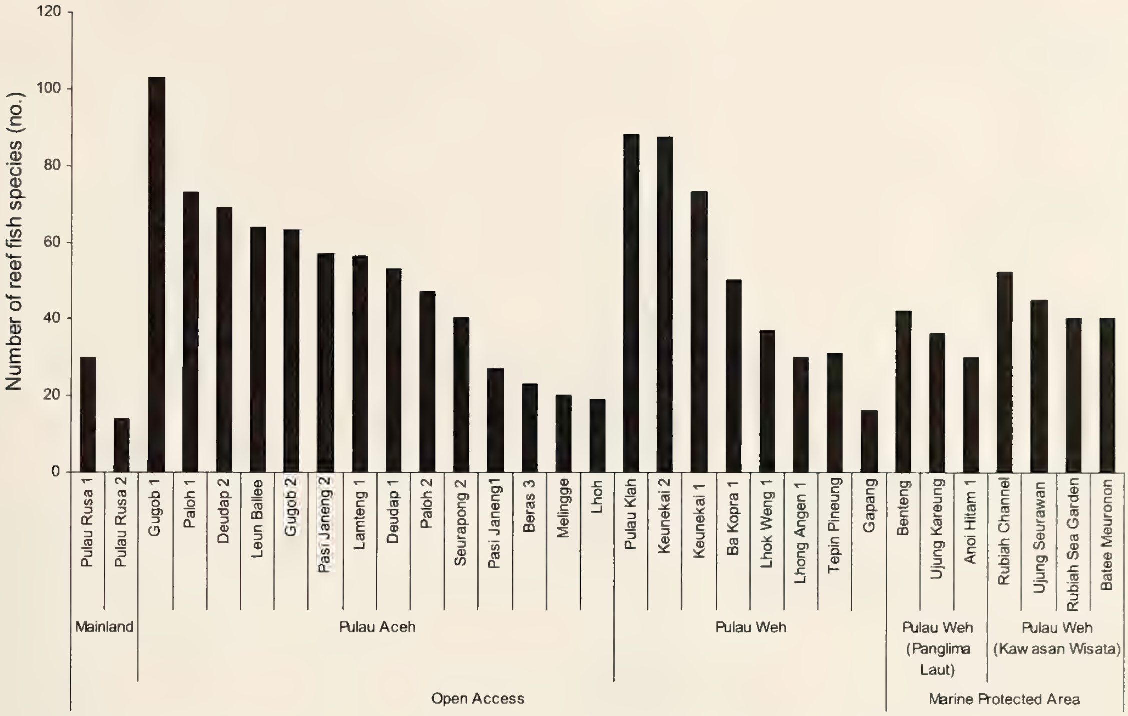


Figure 5. Reef fish species richness in within 3 geographic regions (Mainland, Pulau Aceh, Pulau Weh) and 3 management zones (Open Access, Kawasan Wisata, Panglima Laut) in northern Aceh, Indonesia.

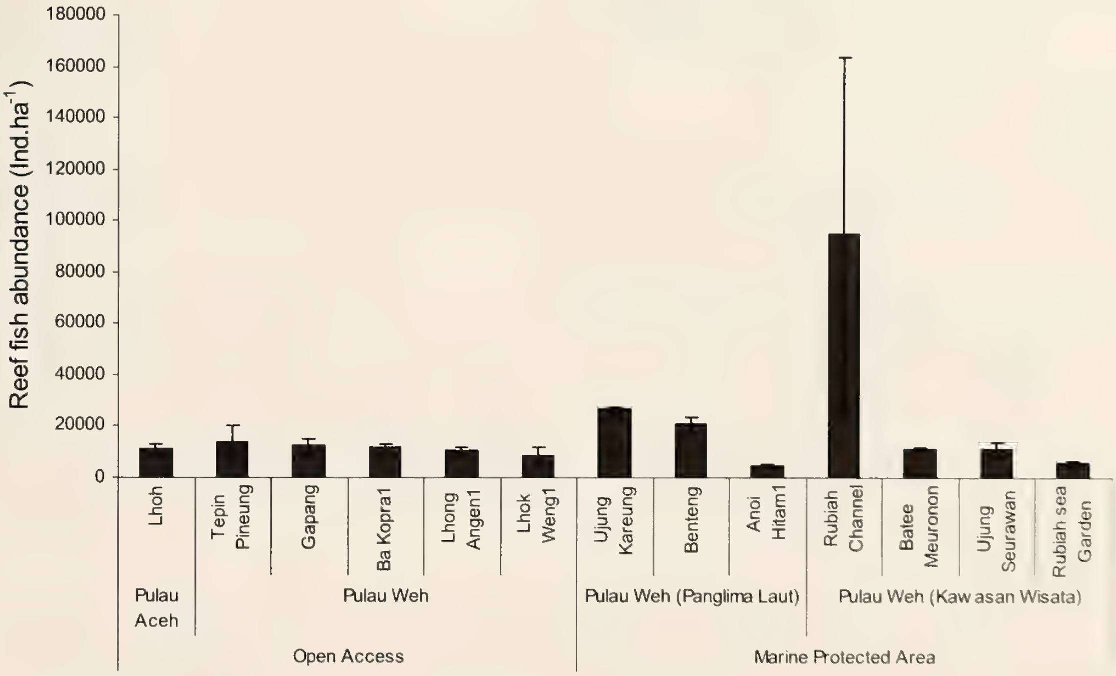


Figure 6. Reef fish abundance (ind.ha-1) (mean ± SE) within 2 geographic regions and 3 management zones (Open Access, Kawasan Wisata, Panglima Laut) in northern Aceh, Indonesia.

The one clear pattern was a higher abundance of overturned colonies growing in unconsolidated substratum below 2 m. Corals firmly attached to solid substratum were largely unaffected by the force of the waves at all sites: damage to these colonies included occasional broken branches (Fig. 2C), presumably as a result of impacts with mobile debris, but very few colonies were dislodged. In contrast, corals growing in unconsolidated substrata, such as sand or rubble, suffered much greater damage: in these habitats many colonies were overturned (Fig. 2D), buried (Fig. 2F), or transported, often over large distances (Fig. 2G). Despite this damage at depth, where coral assemblages were healthy prior to the tsunami, coral cover remained high, and there was little apparent loss of ecological diversity or function.

This type of damage is very different to that observed following large storms, such as hurricanes. While hurricane damage to reefs is also patchy (Woodley et al., 1981), it is unusual for shallow reefs to escape damage over large scales following hurricanes (Hughes and Connell, 1999). Furthermore, fragile morphologies, such as branching and tabular corals, are generally disproportionately affected when compared to massive colonies following hurricanes. A number of features of tsunamis are relevant for explaining this difference. In wind waves, most energy is contained near the surface, and wave-induced water motion decays exponentially with depth (Yeh et al., 1993). In contrast, in a tsunami, water is in motion throughout the entire water column (Yeh et al., 1993). We hypothesise that the initial run down of the tsunami, along with the first wave of the tsunami train, excavated unconsolidated substrata from around the bases of unattached colonies, making them susceptible to displacement when inundated by the subsequent waves. The differential damage to unattached massive colonies at depth appears to be a unique feature of tsunamis disturbance and explains the dominance of massive colonies in tsunami deposits on land (Baird et al., 2005).

An interesting feature of our analysis was that transects with high proportions of up-turned coral did not necessarily have high proportions of broken live coral or recently dead coral. This suggests that the type of damage observed at a site is strongly influenced by what coral species are present. For example, the higher proportion of broken corals on reef crests on Pulau Aceh and mainland reefs compared with Pulau Weh was probably the result of high cover of *Heliopora* (unpublished data), which has a brittle skeleton prone to breakage from mobile debris. *Acropora* colonies, in contrast, did not appear prone to breakage, and were very rarely up-turned, consequently, sites where these species were abundant, such as in the shallow on Pulau Weh had few broken corals. Similarly, large thickets of *Acropora muricata* albeit recently killed (Fig. 2B), remained intact, despite an estimated flow height at the coast of over 15 m (Borrero, 2005) at this site. It is, therefore, surprising that damage to *Acropora* colonies was so prominent in the Seychelles, more than 3000 km from the epicenter of the earthquake, where the maximum wave height was 1.24 m (Hagan et al., 2007).

Ongoing effects of tsunami in April 2005 included an increase in turbidity at many sites where some *Acropora* and faviids were bleached (Fig 2 H), probably as a consequence of prolonged periods of low light (Fabricius, 2005), because there is no indication of recent elevated sea surface temperatures in the area (NOAA, 2005).

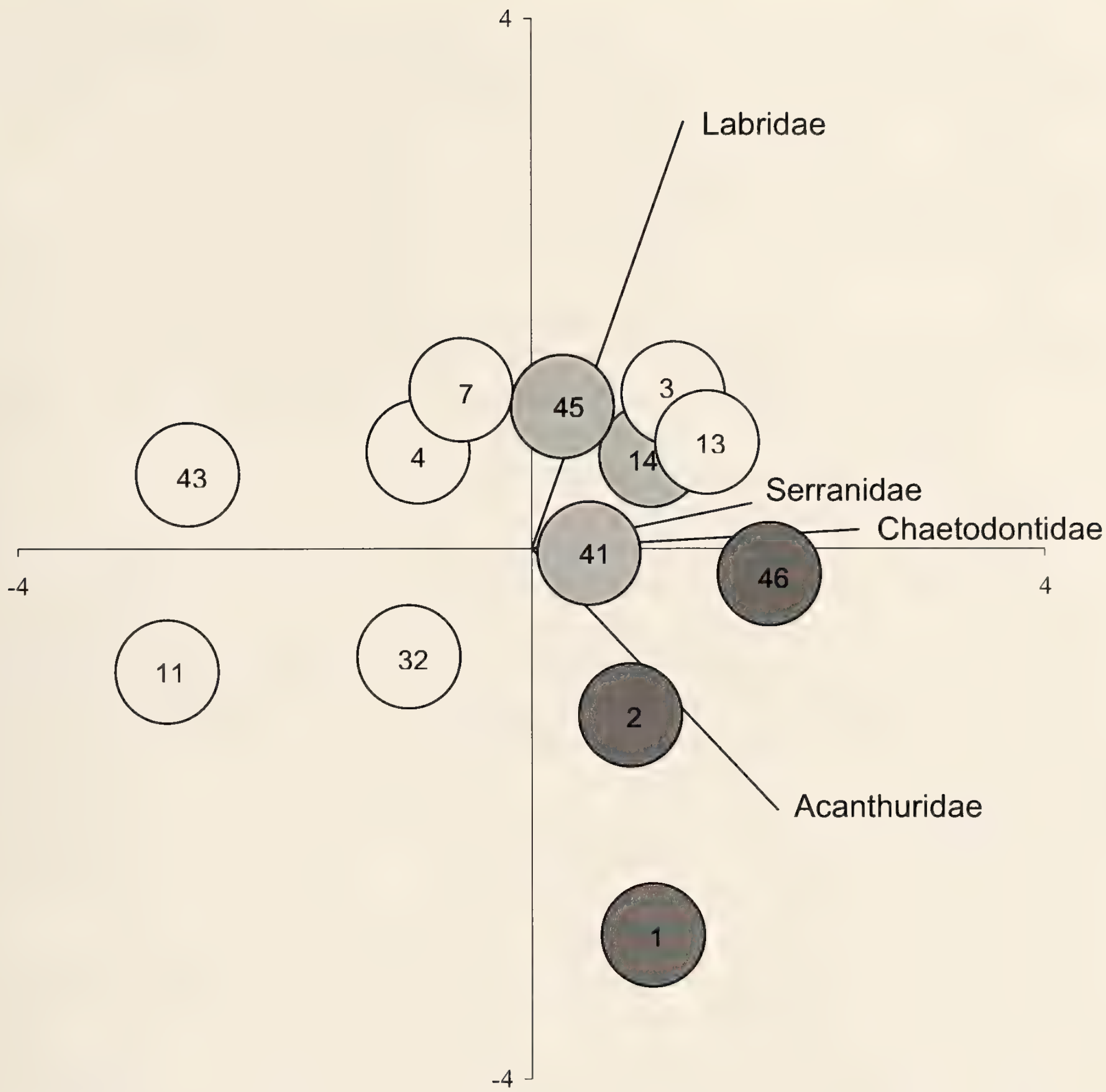


Figure 7. Canonical Discriminant Analysis of coral reef fish assemblages on Acehnese reefs in April 2005. Canonical variates 1 and 2 account for 38.5 % and 26 % of the variation in community structure among all sites and emphasize differences among management regimes (Kawasan Wista = dark grey, Panglima Laut = light grey, and open access = white). Numbers on each centroid correspond with site numbers shown on Figure 1. Circles plotted represent 95% confidence limits around the centroids for each site. Vectors are structural coefficients of response variables, indicating the relative abundance of different families of fishes at each site.

Reef condition varied widely within the region and was strongly influenced by controls on human activity (i.e. management zone). Reef condition was particularly poor in Pulau Aceh (Fig. 4), here long dead colonies and rubble beds were covered with a thick growth of filamentous algae: scenes typical of reefs affected by bombing and cyanide fishing (Pet-Soede et al., 1999). However, even here, where the tsunami was highly destructive on land, there was little evidence of recent coral mortality (Fig. 3C). The most likely cause of low cover at open access sites is destructive fishing practices, such as bombing and cyanide fishing, both of which were prevalent throughout Indonesia in the recent past (Hopley and Suharsono, 2002) and many locals suggested that sediment run-off from inappropriately cleared land may have smothered some reefs (e.g., Lhok Weng – site 11 and Leun Ballee – site 40). On Pulau Aceh, these practices have caused a phase shift (e.g. Hughes, 1994) from corals to algae which the tsunami may have exacerbated with an influx of nutrients and the prospects for recovery of these reefs in the short term are not good.

Given the intensity of the Sumatra-Andaman tsunami, it is again surprising that there was no clear evidence of disturbance to the reef fish assemblages. Tsunamis have the potential to affect fishes by displacing individuals or washing them ashore, as has been observed during severe tropical storms (e.g., Walsh, 1983). Local villagers reported that many small fishes had been washed ashore at Palau Weh immediately after the Sumatra-Andaman tsunami (Allen, 2005). However, it is the disturbance to benthic reef habitats, such as high coral mortality and major alterations in the physical and biological structure of benthic reef habitats, which are most likely to have the greatest impact on coral reef fishes (Wilson et al., 2006). Declines in the abundance of fishes following extensive depletion of hard coral are common (e.g., Sano et al., 1987; Jones and Syms, 1998; Booth and Berretta, 2002; Munday, 2004; Pratchett et al., 2006), though there can be a significant time lag between the loss of habitat and a reduction in fish numbers. For example, Pratchett et al. (2006) detected no change in the abundance of obligate corallivorous cheatodontids, despite a 90% decline in coral cover following coral bleaching, 4 months after the event, which suggests that cheatodontids may take longer than this to starve or relocate. Consequently, the low abundance of cheatodontids at open access sites may indicate that the low coral cover at these sites predated the tsunami. Given that we detected no major change in benthic habitats from the tsunami, as described above, it is, therefore, also highly unlikely that reef fishes were adversely affected by the tsunami. While significant spatial variation in the overall abundance and species richness of coral reef fishes among sites was apparent, this was not attributable to differential affects of the tsunami. For example, the overall abundance of fishes was much higher at Teupin Pineung (site 43), where damage to corals was most pronounced, compared to Anoi Hitam 1 (site 41), where there was very little damage to corals. However, without data from before the event, such conclusions must be treated cautiously.

The relative abundance of some coral reef fishes, especially the Acanthuridae, Serranidae, Labridae and Chaetodontidae, was higher within the Kawasan Wisata (which is closed to all but line fishing) when compared to open access and Pang Lima Laut sites suggesting management has been effective at protecting some species, in particular, those

often caught with nets (Russ, 2002). However, total abundance of reef fish did not vary between management zones, and heavily targeted fishes, such as lethrinids, were in low abundance at all sites. Clearly, management of the Kawasan Wisata could be improved, and there was occasional evidence of breaches of regulations, such as discarded nets. However, comparisons among management zones are confounded by differences in the aspect and benthic habitats of regulated areas versus open access areas. The two existing regulated areas, the Kawasan Wisata and Panglima Laut, are both located on the north-east side of Palau Weh. In addition, there is little true reef development on Pulau Weh: in the shallows, corals grow attached to large rocks; at depth *Porites* bombies which can grow in sand are dominant (unpublished data). In contrast, reefs on Palau Aceh and the mainland are true fringing reefs with potentially greater habitat diversity. This may explain why species richness of fishes within the Kawasan Wisata and Panglima Laut was often lower compared to open access areas. Responses of fishes to protection from fishing are influenced by many complex factors, including the size of reef, the structure of reef fish populations, the proximity of other reefs and the level of compliance with protection regulations (Babcock et al., 1999; McClanahan and Mangi, 2000; Jennings, 2001; Shears and Babcock, 2003; Cinner et al. 2005). Nonetheless, MPAs are gaining increasing acceptance among scientists as one of the few effective ways of managing fisheries of coral reef species (Russ, 2002), and may be critical in making reefs more resilient to acute natural and anthropogenic disturbances (Bellwood et al., 2004).

CONCLUSIONS

Few natural events can compare in scale and intensity to the Sumatra-Andaman tsunami, yet direct damage on reefs was surprisingly limited, and trivial when compared to the clear loss of coral cover where human access has been uncontrolled. The extent of the damage on land, and the tragic human cost should not distract attention away from the perennial problems of marine resource management in Indonesia: improving water quality, reducing fishing pressure and sensible coastal development (Bellwood et al., 2004). Neither the conservation priorities nor the risks to reefs have been changed by the tsunami and it is vitally important that resources are not directed to short term, small scale rehabilitation programs which will not reverse long term declines in reef condition (Hughes et al., 2005). The political good will and the financial resources the tsunami has generated should rather be used to build sustainable economies and just societies that will provide long term security for the people of Aceh and beyond.

ACKNOWLEDGEMENTS

We thank S. Connolly, T.P. Hughes, A. Helfgott and M.J. Marnane for comments on the manuscript. Nurma of Oong Bungalows provided wonderful support in the field. This study was funded by USAid and the Australian Research Council.

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THE INFLUENCE OF THE INDIAN OCEAN TSUNAMI ON CORAL REEFS OF WESTERN THAILAND, ANDAMAN SEA, INDIAN OCEAN.

BY

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ABSTRACT

Coral reefs of the west coast of Thailand were minimally affected by the Indian Ocean tsunami of December 26, 2004. Results of rapid assessment surveys prior to the present study revealed that only 13% of 174 sites visited along the west coast of Thailand were severely damaged with 60% of sites showing little or no damage.

These preliminary results were confirmed in the present study by an evaluation of 17 long-term monitoring sites where reef assessment had been regularly made over the last 15-25 years. Only four of these sites showed marked damage with reductions of coral cover in the order of 5-16%, though it was estimated that coral cover had been reduced by approximately 40% on the southwest tip of Pai Island in Krabi Province where long-term monitoring had not been carried out prior to the tsunami. At impacted sites, damage consisted of overturned massive corals, broken branching corals and smothering of corals by sediments and coral rubble with these effects being greatest in shallow waters. No clear patterns were observed in terms of coral diversity at damaged locations pre- and post- tsunami.

Overall damage was extremely localized affecting only small sectors of reef which were exposed to the full force of the tsunami waves. It is estimated that damaged sites will recover naturally in a time span of 5-10 years provided there is no major setback such as bleaching-induced coral mortality.

INTRODUCTION

The effects of hurricanes and cyclones are well documented in the literature (Hughes, 1993) but there is little or no reference to the effects of tsunamis on coral reef ecosystems despite the fact that tsunamis have been generated in the coral seas around Sumatra and the Andaman and Nicobar Islands in the past (Bilham, 2005). At approximately 09.55h on 26 December, 2004, during a high water spring tide, a series of tsunami waves struck the west coast of Thailand following a major earthquake registering 9.3 on the Richter scale off northwest Sumatra (Stein and Okal, 2005). Four days later, the Thai Ministry of Natural Resources and Environment and staff from nine national universities launched a rapid survey of marine habitats along the entire 700km coastline

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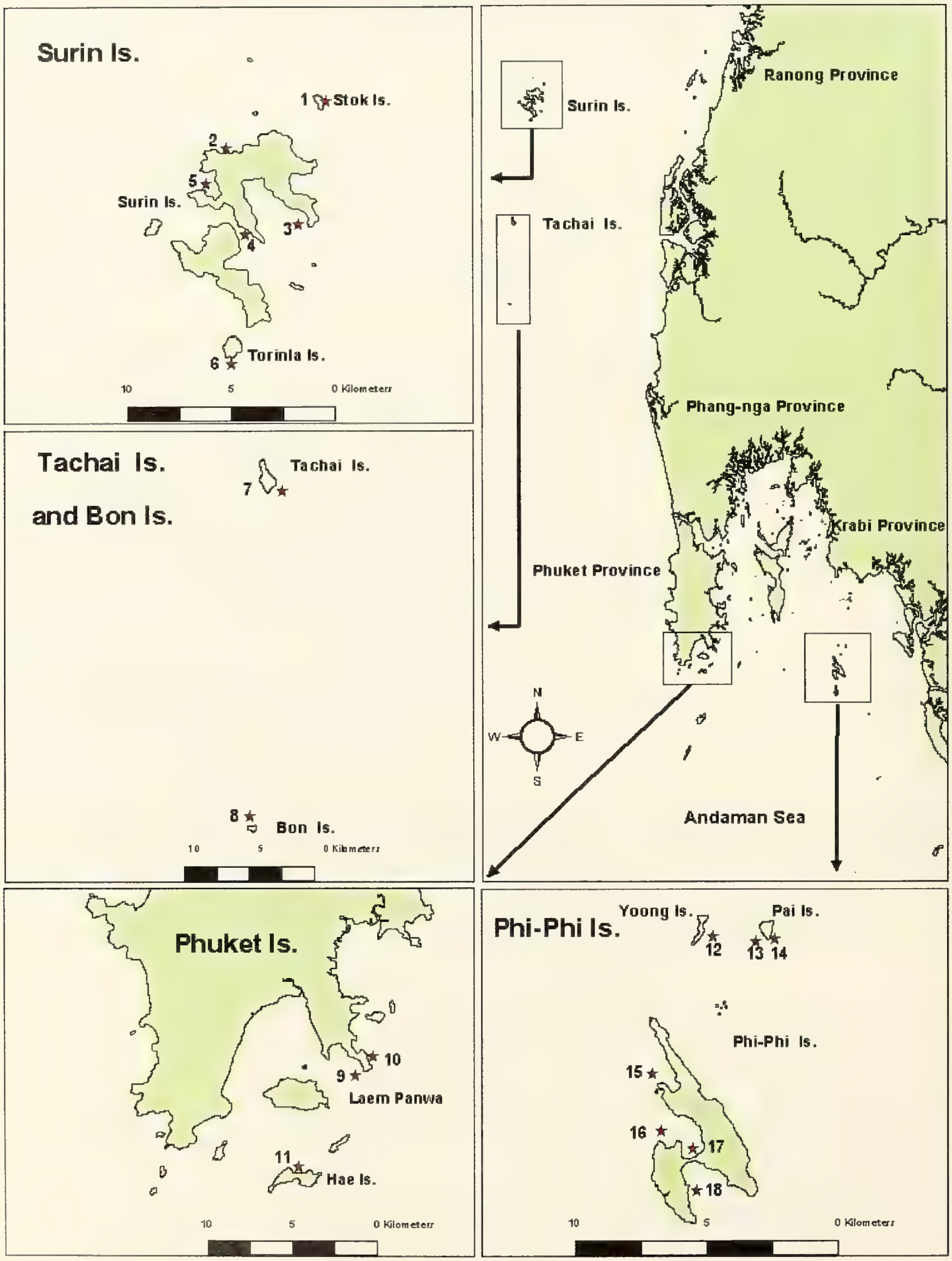

Figure 1. Maps showing the location of monitoring sites 1-18 along the west coast of Thailand.

of west Thailand. They visited coral reefs at 174 sites and noted that up to 105 sites were unaffected or showed very little damage while 30 showed low level damage (11-30% coral cover affected), 16 displayed moderate damage (31-50% coral cover affected) and 23 were severely damaged (>50% coral cover affected) (Department of Marine and Coastal Resources, 2005, Satapoomin et al., 2006).

This initial survey concluded that the northernmost coastline (Ranong, and Phang-nga Provinces) and its offshore islands (Surin and Similans) were more severely impacted than the south (e.g., Phuket, Krabi except Phi Phi Island, Trang and Satun) with shallow reefs on wave-exposed islands and shorelines being more vulnerable to wave-induced damage. The destructive impact of the tsunami appeared to be dependent on the degree of exposure to the waves, the surrounding sea bottom topography and depth of water over the reef.

Unlike many other countries in the region, Thailand boasts a valuable long-term data base on coral cover and diversity of fringing reefs that characterize the coastline bordering the Andaman Sea. This data base includes information from shallow reef slopes (Phongsuwan and Chansang, 1992) and intertidal reef flats (Brown et al., 1990, 2002, Brown and Phongsuwan, 2004) that have been monitored regularly over the last 10-25 years. Using this data and information from the rapid assessment survey of 2005, this paper evaluates the impact of the 2004 tsunami and predicts the likely outcome for reefs that were severely damaged.

METHODS

Figure 1 and Table 1 describe the locations of 18 monitoring sites visited in the study. Seventeen of these sites are long-term monitoring locations with over 10 years worth of regular coral-reef surveillance data while one was a site that had been severely affected by the tsunami but which had not previously been subject to regular monitoring. All sites, apart from site 10 on the Laem Pan Wa Peninsula of southeast Phuket, were reef slopes. Site 10 was an intertidal reef flat that extended approximately 150m from the shoreline and was dominated by massive poritid and faviid corals with branching species (*Acropora hyacinthus, Acropora aspera, Acropora pulchra, Acropora humilis* and *Pocillopora damicornis*) at the reef edge. Of reef-slope sites all locations, apart from sites 8 and 15, were upper reef slopes at depths ranging from approximately 3-7m. Depths at sites 8 and 15 were approximately 10m. Reef slopes were generally mixed communities often dominated by either massive (*Porites lutea*) or branching (*Porites rus, Porites nigrescens*) poritid corals, together with a variety of branching *Acropora* spp.

Permanently marked 100 m long transects, running parallel to the coastline and along a particular depth contour, were monitored using standard methods (Phongsuwan and Chansang, 1992) at all sites apart from site 10. At the latter location a series of 12 permanently marked 10m long reef transects were established across the reef flat in 1979 at 10 m intervals (Brown et al., 1990). For the purposes of this study, only the four outer reef flat transects were considered. Measures of coral cover and diversity (H_1^c) were calculated according to the methods of Loya (1972) at all locations.

Tidal data were collected from the Ko Taphao Noi tide gauge located on the eastern side of the Laem Panwa Peninsula, Phuket. Hourly sea levels were computed from the records for this station which are held at the University of Hawaii/National Oceanographic Data Center Joint Archive for Sea Level.

Table 1. Showing names, positions and site numbers of coral-reef monitoring stations.

Site number	Site name	Latitude	Longitude
SURIN ISLANDS			
1	Stok	9°28.486'N	97°54.375'E
2	North Surin	9°27.290'N	97°51.872'E
3	North Mayai	9°25.473'N	97°53.864'E
4	Park Front	9°24.923'N	97°52.656'E
5	Mai-ngam Bay	9°26.309'N	97°51.199'E
6	South East Torinla	9°22.038'N	97°52.099'E
OFF-SHORE ISLANDS			
7	Tachai	9°17.508'N	98°19.879'E
8	Bon	9°43.486'N	98°06.587'E
PHUKET AREA			
9	Laem Panwa West	7°47.956'N	98°24.526'E
10	Laem Panwa East	7°48.539'N	98°24.692'E
11	Hae Island	7°44.725'N	98°22.740'E
PHI-PHI ISLANDS			
12	Yoong	7°48.826'N	98°46.615'E
13	South West Pai	7°48.956'N	98°47.647'E
14	East Pai	7°48.970'N	98°48.050'E
15	Phi-Phi-Lana	7°45.845'N	98°45.960'E
16	Lodalum	7°44.764'N	98°46.360'E
17	Yongkasem	7°44.517'N	98°45.915'E
18	Phi –Phi-Tonsai	7°43.352'N	98°46.364'E

RESULTS

Relatively few of the long-term monitoring sites showed any effects of the tsunami with the majority of sites along the Thai coastline appearing in exceptionally good condition after the event (Fig. 2). The main damage on reefs affected by the tsunami included overturned massive corals (Fig. 3a), broken branching corals (Fig. 3b), and covering of live coral surfaces by sediments (Fig. 3c).

Figure 2. A mixed coral community on the upper reef slope at Site 5 in the Surin Islands after the tsunami.

The damage caused was extremely localised with overturned corals at one point and untouched corals only metres away. On sheltered intertidal reef flats where there had been extensive stands of dead branching *Acropora aspera* on the reef edge, as a result of lowered sea level in 1997-98, broken branches of dead *Acropora* were carried inshore by the tsunami waves to cover highly localised areas of living massive species. In some cases partial mortality of living coral surfaces resulted from smothering and abrasion by these dead coral branches. Of the seventeen 10 m transects surveyed on the intertidal reef flat only one was affected in this way, highlighting the very limited and localised nature of damage caused by the tsunami waves.

Figure 3. Types of tsunami-related damage to coral reefs (**a**) Overturned massive *Porites* colony (**b**) verturned and broken *Acropora florida* colony (**c**) Sediment-covered *Porites* colony.

Percentage of coral cover monitored over time at selected sites is shown in Table 2 and Figure 4. Sites shown in Table 2 represent locations where cover data have been collected irregularly over the last 16 years. Figure 4 illustrates changes in coral cover at five sites where monitoring has been carried out on a more frequent basis over a 16-26 year period. Lower coral cover between pre- and post-tsunami surveys was noted at sites 6,7,15 and 16 (Table 2). These were also sites where tsunami-related coral damage had been observed. No quantitative data are available pre-tsunami for site 13 though coral cover estimates from manta surveys suggest an approximate coral cover of 40-50% in mid 2004 (Phongsuwan and Arunwattana, 2005). Significant damage, in terms of overturned massive corals and broken *Acropora* branches, was noted at this wave-exposed location and these effects are reflected in the low cover observed after the tsunami. At sites 15 and 16, reduced coral cover was attributed to damage caused by increased sediment loads, generated by the tsunami waves, which smothered coral tissues.

Table 2. Percentage coral cover over time at selected monitoring stations. (n/a = data no available)

a) Surin Islands

Site No.	1989	1990	1993	1998	2001	2005
1	n/a	37.7	n/a	11.7	16.9	27.1
2	50.0	60.0	29.0	19.1	22.6	25.0
4	42.0	49.7	36.0	15.3	20.2	48.2
6	n/a	48.7	n/a	32.4	n/a	23.6

b) Offshore Islands

Site No.	1988	1989	1995	2001	2005
7	n/a	5.4	n/a	40.3	32.4
8	46.0	n/a	51.3	30.1	28.0

c) Phi-Phi Islands

Site No.	1988	1991	1995	1997	2000	2003	2005
12	n/a	n/a	n/a	n/a	28.5	n/a	37.2
13	n/a	n/a	n/a	n/a	n/a	n/a	13.1
14	n/a	n/a	n/a	n/a	28.2	n/a	44.2
15	28.3	n/a	34.2	n/a	29.1	n/a	14.5
16	n/a	n/a	n/a	n/a	n/a	28.0	23.8
17	n/a	n/a	30.1	35.8	29.4	30.6	34.2
18	63.5	68.6	50.5	59.4	47.2	52.8	51.6

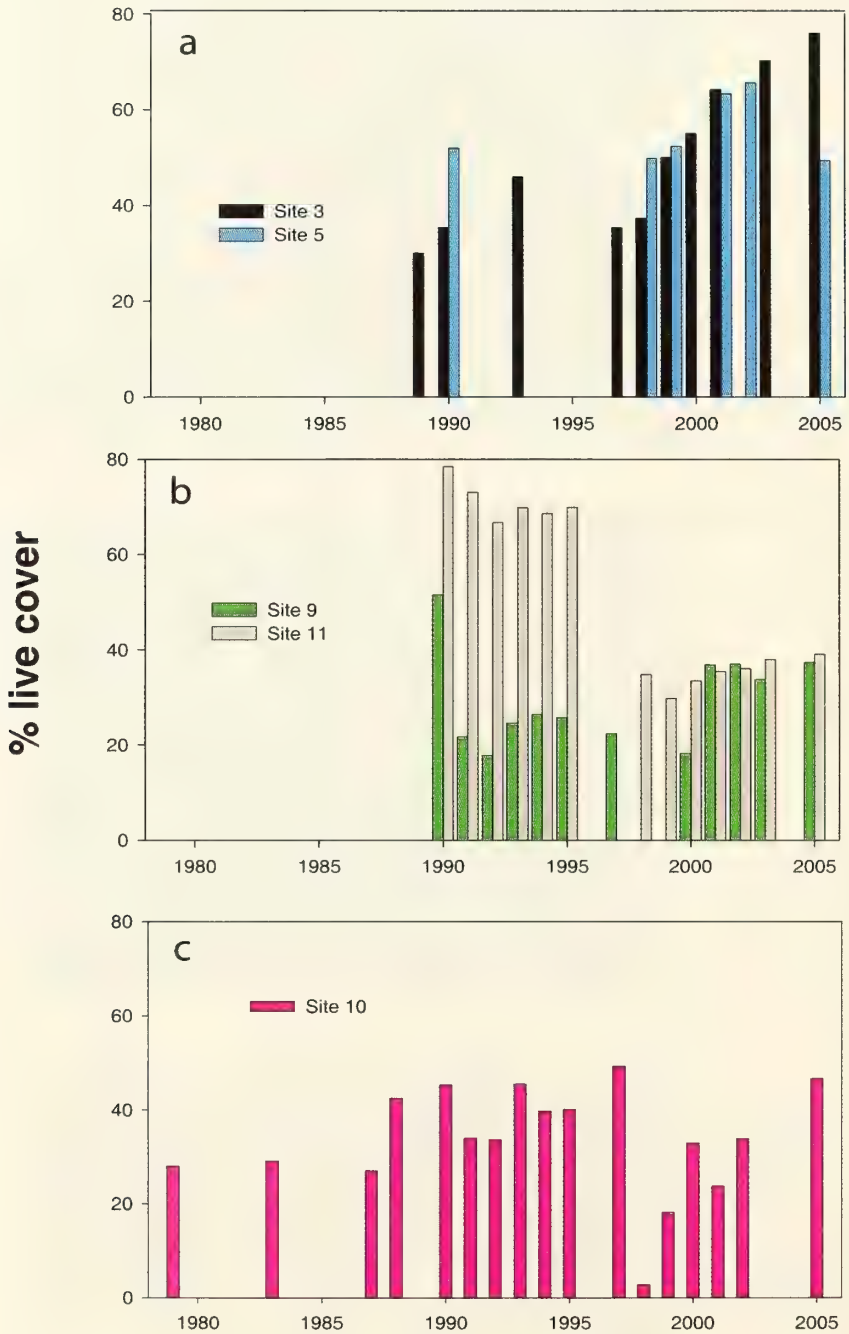

Figure 4. Changes in percentage coral cover over time at a) Sites 3 and 5 b) Sites 9 and 11 c) Site 10.

In Figure 4a, a decrease in coral cover in 2005 is evident only at Site 5 but this cannot be attributed to the tsunami and is most likely related to a mild bleaching event in 2003. At site 3, coral cover is as high in 2005 as has ever been recorded at this location since 1989. Figure 4b shows no loss of cover as a result of the tsunami at sites 9 and 11 although there was a marked drop in coral cover at site 9 between 1990 and 1991 as a result of an extensive bleaching event in 1991. There has been very little recovery at this location in subsequent years. At intertidal site 10, coral cover was lowest in 1997-98 during a period of exceptionally low sea level. Field observations at this location revealed no physical damage as a result of the tsunami and this was reflected in the high coral-cover values of 2005.

Generally diversity indices showed very little change over time at both affected and unaffected sites (data not shown) with no clear patterns emerging at sites affected by the tsunami.

DISCUSSION

The Indian Ocean tsunami of 2004 clearly had a limited effect upon the coral reefs of the Andaman Sea coast of Thailand. Remarkably, there appears to be few references to the effects of tsunamis on coral reefs in the literature despite a history of repeated tsunamis in the Indo-Pacific region. For example, a total of 35 tsunamis have been estimated to have impacted the Indonesian archipelago since the Krakatau tsunami of 1833 (Carey et al., 2001) while significant tsunami waves were reported following earthquakes at Car Nicobar in 1881 and in the Andamans in 1941 (Bilham et al., 2005). Coral reefs were mentioned in a report of a tsunami initiated as a result of an earthquake in the Philippine Fault Zone in S.E Mindanao in 1992 but only in terms of their ameliorating effects in reducing the wave height finally reaching the shore (Besana et al., 2004).

Although the heights of the tsunami waves are not reflected in the tidal measurements obtained for the relevant period at Ko Taphao Noi, Harada (2005) estimates tsunami wave heights to have been approximately 10m on the mainland inshore from sites 7 and 8, 3 m at sites 9, 10 and 11 and 5 m at sites 15 and 16. These heights were measured on site within four days of the arrival of the tsunami waves. Coral reef damage appears to have been mainly restricted to sites on the west-to- southwest sides of islands which are frequently exposed to southwest monsoon influences. Coastal topography and aspect of site similarly played an important role in influencing tsunami-related damage to coral reefs in northern Sumatra in December 2004 (Baird et al., 2005). While poorly attached massive corals at depth were displaced in Sumatra (Baird et al., 2005) damage was mainly restricted to shallow reef sites in Thailand.

At the few locations where negative impacts were observed along the Thai coastline, the type of damage noted was similar to that of hurricanes and cyclones with broken branching corals (Woodley et al., 1981, Woodley, 1993; Rogers, 1993) and dislodgement of often weakly attached massive colonies (Massel and Done, 1993) in shallow waters. Similar dislodgement of large colonies of *Acropora palifera* has been

noted in Flores in eastern Indonesia following a tsunami (Tomascik et al., 1997). The extremely localized nature of the damage observed in the present study was also similar to that noted during hurricanes with only sectors of a reef affected (Woodley et al., 1981; Rogers, 1993) where susceptibility varied markedly between different coral species (Bythell et al., 1993). At impacted sites in Thailand, branching *Acropora* species were particularly susceptible (both plate-like varieties and arborescent forms) as were weakly attached massive *Porites* colonies.

There appears to be very little mention of deleterious effects of sediment mobilisation on coral reefs as a result of hurricane damage in the scientific literature. Rather, hurricane-mediated flushing of sediments has been described as benefiting coral reef development (Hubbard, 1986, 1992; Hillis and Bythell, 1998). Although sedimentation has caused some coral mortality at two sites around Phi Phi Island, sediment effects as a result of the tsunami have been limited. There are at least two reasons why this should be the case. Firstly, many of the corals which are dominant on Thai reefs are capable of efficient removal of sediment from their surfaces (Stafford-Smith, 1993) and secondly, flushing as a result of the tsunami waves and the spring tides occurring at the time would aid cleansing of coral surfaces. Indeed, improved water quality was noted at many sites following the tsunami along the Thai coastline probably as a result of strong flushing (Department of Marine and Coastal Resources, 2005). In Banda Aceh localized sediment damage to corals was reported after the tsunami, together with changes in sediment regimes that caused increased turbidity around coral reefs (Baird et al., 2005).

Where limited tsunami-induced reef damage has occurred on the Andaman Sea coast of Thailand, it is likely that natural recovery will take place within the next 3-5 years at low impact sites and within 5-10 years at locations with severe damage. The reasons for such a confident prognosis arise from three factors: first the exceptionally high growth rates of dominant corals in the region (Scoffin et al., 1992; Lough and Barnes, 2000); previous evidence of rapid reef recovery following damage from storm surges (Phongsuwan, 1991), sedimentation and lowered sea levels (Clarke et al., 1993; Brown et al., 2002; Brown and Phongsuwan, 2004); and the present generally good condition of reefs in the area. Such a rapid recovery does, however, depend on reefs not suffering from widespread mortality from other sources such as elevated sea temperatures. Although Hoegh-Guldberg (2004) has predicted, from theoretical models, annual bleaching and high coral mortality on the Thai coastline from the late 1970's onwards, the only marked bleaching mortality that has actually taken place to date occurred in 1991 and 1995 with very limited bleaching since these events (Phongsuwan, unpubl).

ACKNOWLEDGEMENTS

We would like to acknowledge the efforts of Government of Thailand and Thai University staff and volunteers in the rapid assessment survey of the Thai coastline and also the support of B. E. Brown's post-tsunami monitoring of selected reef sites by the Natural Environment Research Council, United Kingdom.

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EFFECTS OF THE TSUNAMI OF 26 DECEMBER 2004 ON RASDHOO AND NORTHERN ARI ATOLLS, MALDIVES

BY

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INTRODUCTION

We report our observations on Radhoo Atoll, located in the Maldives, during the tsunami of 26 December 2004. Observations were made on a marginal reef island and from a small boat in the lagoon of the atoll. Post-tsunami changes on some islands and reefs of Rasdhoo and nearby Ari Atoll are described.

SETTING

The Maldive archipelago is about 1,000 km long and up to 150 km wide encompassing an area of 107,500 km2 (Fig. 1). Some 0.3% of this area is formed by 1,200 islands, only 10 of which are larger than 2 km2. The maximum land elevation is 5 m above present sea-level. Geomorphologically, the Maldives form a N-S-trending double row of 22 atolls, separated by the Inner Sea up to 450 m deep. The Maldives are bounded bathymetrically by the 2,000 m contour, i.e., the archipelago rises steeply from the surrounding Indian Ocean seabed.

The geological development of the Maldives since the early Tertiary was recently summarized by Purdy and Bertram (1993) and Belopolsky and Droxler (2003). Whereas the knowledge of the Tertiary development is well documented based on ODP drill sites and exploration wells and seismics, the knowledge on the Quaternary evolution of the Maldives is quite limited (e.g., Woodroffe, 1992; Kench et al., 2005).

The climate is monsoon-dominated. During the wet monsoon from April to November winds blow to the NE, during the dry monsoon from December to March winds blow to the SW. Annually, most strongest and frequent winds blow towards the E (Fig. 1). Due to their proximity to the equator, the Maldives are largely storm-free. Water temperatures fluctuated annually between 28-30 °C during the past several years (COADS, grid 3-5°N, 72-74°E). Annual precipitation rates ranged from 1,000-2,000 mm during the 20th century (GHCN, Minicoy, Laccadives). The tidal range in the Maldives is 0.5-1 m.

Rasdhoo Atoll is located in the western row of Maldivian atolls. It is a comparably small atoll with a maximum diameter of 9.25 km and a size of 62 km^2 (Fig. 2). The marginal reef is near-continuous and surface breaking. There are 5 sand and

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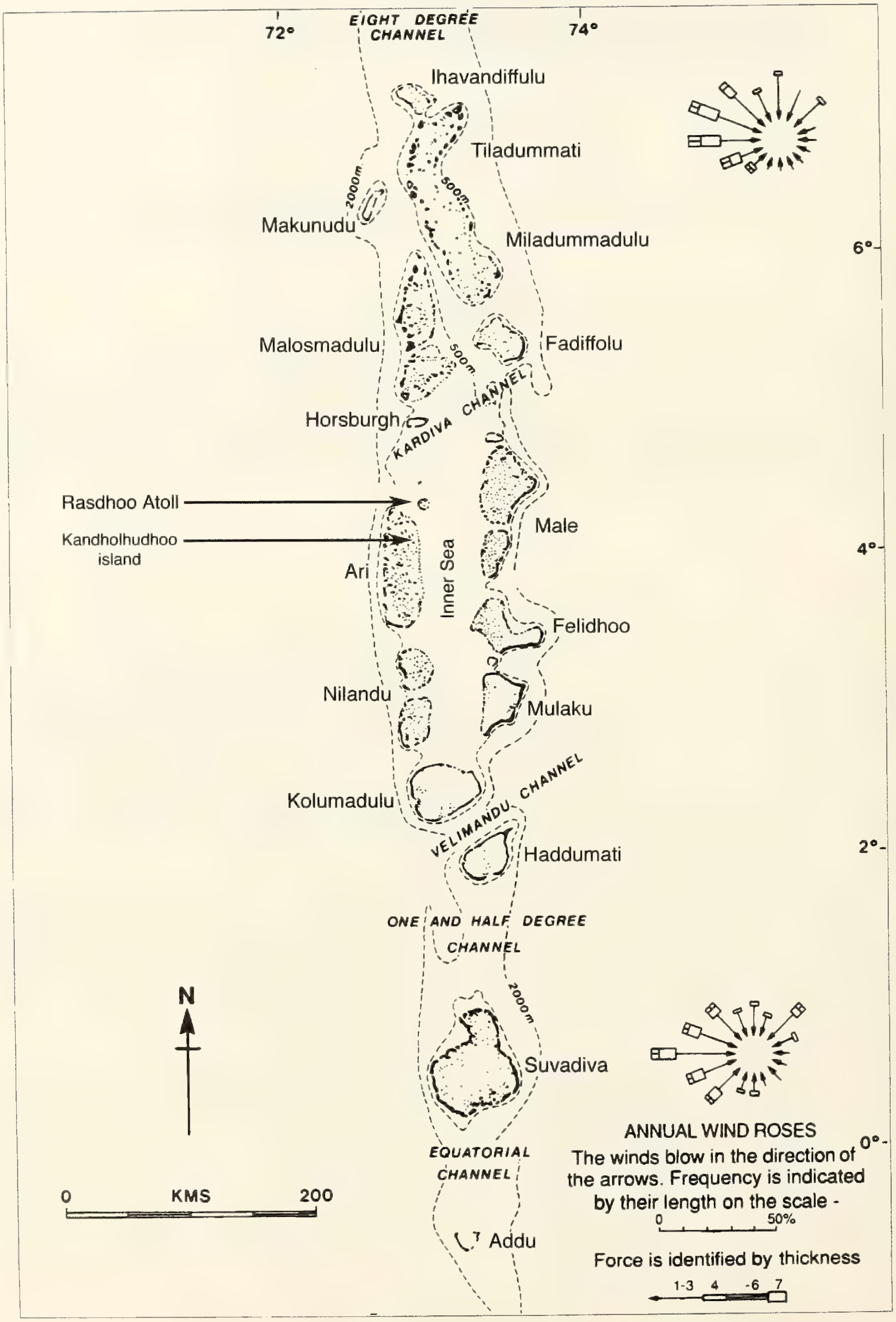

Figure 1. Map of the Maldive archipelago including wind data (after Purdy and Bertram, 1993). Upper arrow points to Rasdhoo Atoll. Lower arrow below points to location of Kandholhudhoo island where post-tsunami observations were made.

rubble islands on the marginal reef named Kuramathi, Rasdhoo, Madivaru, Madivaru Finolhu, and Veligandu, from west to east. Three channels through the marginal reef connect the interior lagoon with the open ocean and Inner Sea, respectively. The lagoon is up to 40 m deep and there are about 40 lagoonal coral patch reefs. Lagoonward of the peripheral reefs, a sand apron is developed, which is widest on the western side of the atoll. In the northern and western lagoon, an elongated ridge of coral and sand is developed, which separates a narrow, up to 10 m deep lagoonal part from the rest of the lagoon. The fore reef slope is very narrow except on the western side of the atoll. The slope ends in an almost vertical drop-off. Previous work at Rasdhoo Atoll includes the coral study of Scheer (1974) who reports 99 species of coral. Early researchers such as Gardiner (1903) and Agassiz (1903) did not visit Rasdhoo Atoll.

Ari Atoll belongs to the largest atolls of the Maldives (Fig. 1). It is 95 km long, 33 km wide at the widest point, and covers an area of 2,300 km^2. The marginal reef is discontinuous with some 40 major passes. The lagoon is as deep as 80 m. Numerous sand

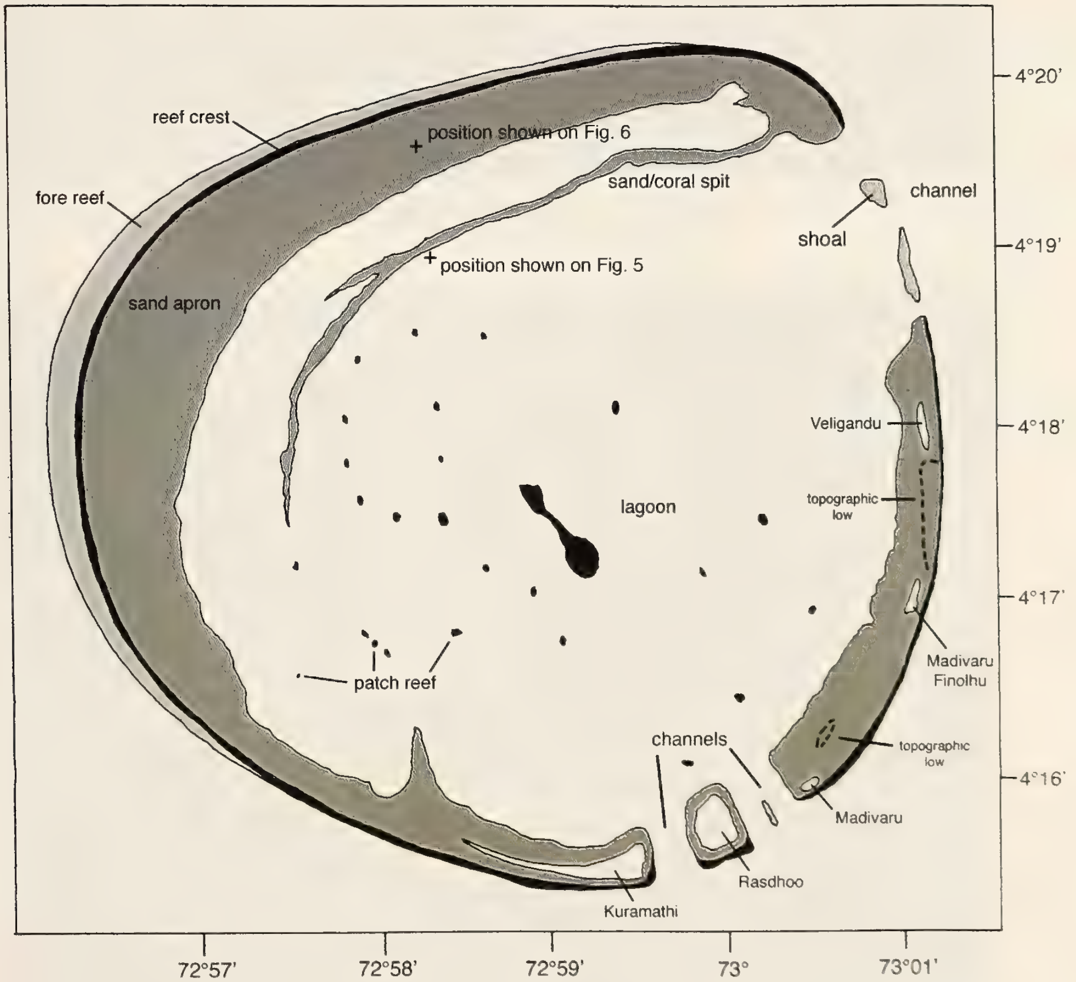

Figure 2. Map of Rasdhoo Atoll drawn from satellite image (from Gischler, 2006). Topographic lows in eastern reef are either locations of collapsed margin or former channels which are in the process of being filled in by sediment.

Figure 3. Nearly flooded sun deck in front of "Kuramathi Cottage" bar. 9:51 a.m., Rasdhoo Atoll.

Figure 4. Flooded path between "Kuramathi Cottage" restaurant and the lagoon. 9:50 a.m., Rasdhoo Atoll.

Figure 5. Lagoon of Rasdhoo Atoll at about 10 a.m. looking north. In the foreground, the long east-west-trending sand/coral spit is seen; water is "boiling" over the sand spit as a consequence of strong currents. The northern marginal reef of the atoll is seen in the background.

Figure 6. Northern margin of Rasdhoo lagoon at about 11 a.m. looking north. The marginal reef can be seen in the background, about 250 m in the distance. Note how lagoon water has turned "milky" as a consequence of fine sediment suspension.

and rubble islands on the marginal reefs and on lagoonal shoals make up 8.3 km2 (Naseer and Hatcher, 2004). Within the lagoon there are about 140 major patch reefs and faroes. Among the early researchers, Agassiz (1903, 103-107) visited Ari Atoll and made geomorphological observations.

CHRONOLOGY

On Sunday morning, 26 December 2004, one of us (R.K.) went to the beach of the atoll lagoon at the tourist resort “Kuramathi Cottage” on Kuramathi island, Rasdhoo Atoll. It was about 9:30 a.m., weather conditions were fine with blue sky and moderate wind from the ENE. Sea-level was unusually low at this moment and it was still falling fast. It even fell below the springtide minimum. For this day, however, the December tide table predicted low tide at 7:12 a.m., high tide at 12:29 p.m., with a tidal range of only 31 cm. After the initial low water, sea-level started to rise rapidly (Fig. 3). It was not a breaking wave coming in; it was merely rising water. At 9:50 a.m. the nearshore areas were already flooded, and the highest water level was reached by 9:53 a.m (Fig. 4). The water level ascended to the foundations of certain buildings, e.g., the Cottage diving school and the Cottage bar; then it started to fall fast. Within ten minutes it fell by two meters. Subsequent rising and falling of the ocean continued for about three hours, probably triggered additionally by seiche-type standing waves inside the atoll lagoon. The amplitude sea-level oscillations decreased with time, and at 1:00 p.m. the level was once again stable.

The other one of us (E.G.) had rented a local boat (dhoni) at the tourist resort “Kuramathi Village” at the E end of Kuramathi island on the morning of 26 December in order to collect surface sediment samples from Rasdhoo Atoll lagoon. After an hour of sampling, around 10 a.m., the dhoni had reached the E-W-trending sand/coral spit, which separates the atoll lagoon in the north. The boat captain was just trying to cross the spit between several coral heads when sea- level fell dramatically so that coral heads were subaerially exposed. It was not possible to measure the fall due to the lack of a reference point, however, sea-level fell by at least 1 m. The water rose again quickly and strong currents caused the water on top of the spit to “boil” (Fig. 5). We were discussing what could have caused this rapid sea-level fluctuation, but nobody on the boat realized what had really happened. We surrounded the sand/coral spit in the west and continued to collect sediment samples to the north of the spit. In order to get samples from the marginal back reef sand apron, E.G. had to swim towards the northern reef (Fig. 6). This task turned out as being very difficult. First, the visibility had meanwhile turned to almost zero because of the intensive sediment suspension. Second, the current direction was frequently changing, presumably due to seiche-type waves that had developed inside the lagoon. For these reasons it was almost impossible to remain on a straight course. We continued sampling, but when we tried to work in the NE channel in the early afternoon we had to stop because of up to 4 m high waves and swells coming into the lagoon. We eventually completed sampling in the eastern lagoon by 3:30 p.m. and returned to Kuramathi. Only then did we learn what had really happened in the morning. The

sediment samples we collected are analyzed meanwhile, and the results are published elsewhere (Gischler, 2006).

EFFECTS ON THE ISLAND

No one was killed or injured on the island of Kuramathi. Some divers and snorkelers had difficulties due to strong currents and poor visibility, but everybody returned safely. There was minor damage of the infrastructure, including some water in three bungalows. The salt-tolerant vegetation along the supralitoral fringe, including the succulent salt bush (*Scaevola* sp.), the screw pine (*Pandanus* sp.), and the coconut trees (*Cocos nucifera*) did not suffer from the flooding. In contrast, flooded breadfruit trees (*Artocarpus* sp.) shed their leaves, but most of them recovered within weeks or months. Parts of the sandy beaches were eroded by the extreme high water, and soil from the island was washed into the atoll lagoon. The long sand bank at the west end of Kuramathi was practically cut in two by the tsunami (Fig. 7). Several hundred m^3 of sand were probably moved when a 10 m wide channel was cut in the sand spit. For months the beaches were constantly polluted by drifting debris washed ashore. The greatest commercial damage was done to the island by the subsequent holiday cancelling by many tourists.

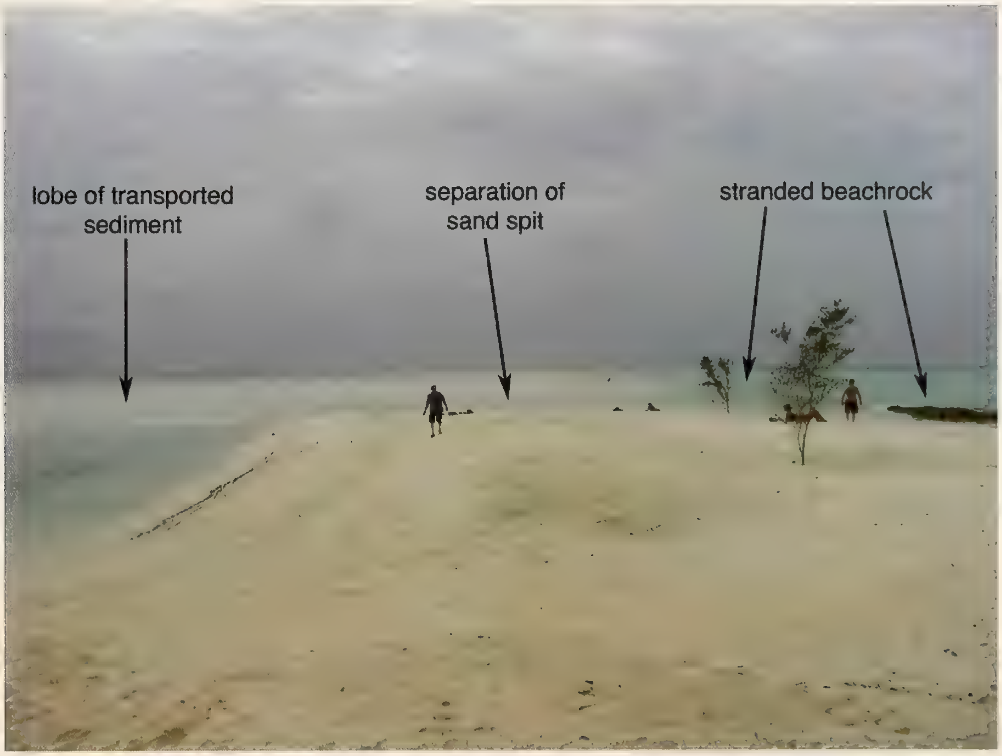

Figure 7. Sand bank at western end of Kuramathi island looking west. Sand bank was separated in two due to the tsunami. Note stranded beachrock at the northern (right) side of picture.

EFFECTS ON THE CORAL REEFS

There were two main stresses for the corals: sedimentation and mechanical stress. The strong water movement created massive sedimentation in the entire reef. Snorkelling one day after the tsunami showed a sediment-loaded reef. Within a few days, however, the reef made a cleaner impression. Most of the sediment was probably washed or actively transported away by the corals from their living surface. The number of broken corals was low. One reason might be the coral species composition after the 1998 bleaching event. During this natural disaster the fragile, fast-growing branched Acroporidae were dramatically reduced in number. At the time of the tsunami, massive-growing corals like Poritidae and Faviidae were dominant. Most of them were able to resist the strong swell.

The situation was different in the atoll channels. Extremely strong currents developed there, which equalized the changing water levels inside and outside the lagoon. Big coral boulders were knocked over by the surge, and a number of the strong *Tubastrea micrantha* corals were broken.

The tsunami had again a different impact on the coral reef around the small island Kandholhudhoo in the northern lagoon of Ari Atoll (04°00,118'N, 72°52,926'E; Fig. 1). The species composition of the Kandholhudhoo reef is remarkable, because it has a high percentage of branched and plate-like Acroporidae. They are mainly growing on unstable coral rubble. Therefore, many plate-like corals were knocked over together with their substrate, and they are in a tilted position now (Figs. 8, 9). Subsequent re-orientation of the tilted corals by special growth patterns of their marginal regions can be observed. A number of branched corals were also knocked over, or parts of the colonies broke away. At one position, in front of a channel, loads of sediment and coral rubble buried the upper part of the reef slope (Fig. 10). Secondary reef damage occurred months after the tsunami, when drifting tree-trunks floated by the Maldives. Those which were swept into shallow reefs broke the corals, and it was difficult to remove the trunks.

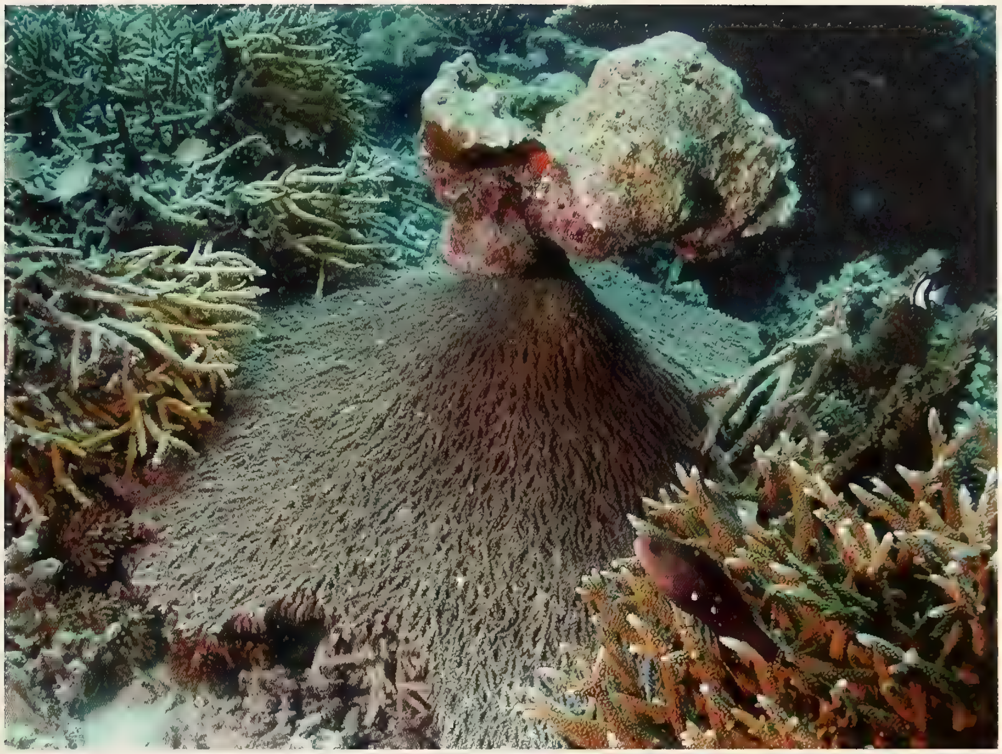

Figure 8. Kandholhudhoo (Ari Atoll), 3 m depth, 20 January 2005. The tsunami swell knocked over this table coral together with its substrate into an upside down position.

Figure 9. Kandholhudhoo (Ari Atoll), 3 m depth, 20 January 2005. Damselfishes (Pomacentridae) seek shelter between the branches of a tsunami-displaced *Acropora*.

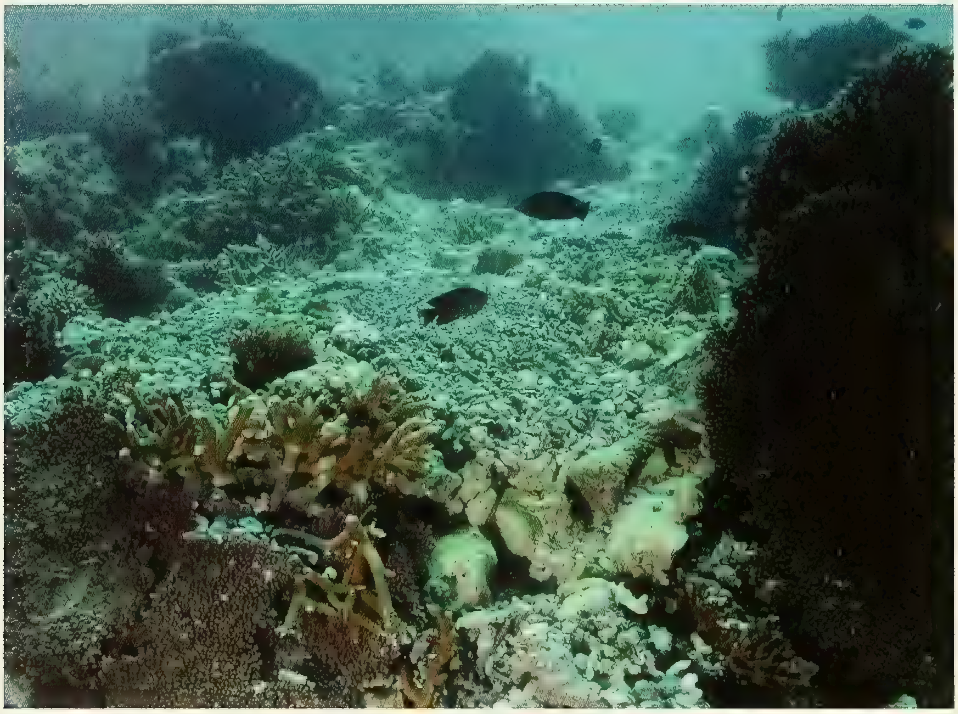

Figure 10. Kandholhudhoo (Ari Atoll), tsunami triggered coral rubble slide down the reef slope. Depth 7 m, 20 January 2005.

SUMMARY

Due to the steep rise of the Maldives from the Indian Ocean sea bed, a considerable amount of energy of the December 2004 tsunami was apparently reflected and prohibited the building of a very high wave, thereby sparing the Maldives a similar catastrophe as, e.g., Sri Lanka or Sumatra. The islands on the eastern atoll chain were most heavily affected. Kuramathi and the other islands in Rasdhoo Atoll (Rasdhoo, Madivaru, Veligandu) were only minimally affected by the December 2004 tsunami, presumably due to the location of Rasdhoo in the western atoll chain and the fact that the marginal reef is almost continuous. The damage to the reefs was related to their exposition, topography, and species composition. In general, the reef damage was not heavy in this area. Diving in northern Ari Atoll showed a similar picture as in Rasdhoo Atoll. The 1998 bleaching event was much more devastating for the reefs in this region than the December 2004 tsunami.

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IMPACT OF THE SUMATRAN TSUNAMI ON THE GEOMORPHOLOGY AND SEDIMENTS OF REEF ISLANDS: SOUTH MAALHOSMADULU ATOLL, MALDIVES

BY

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ABSTRACT

Mid-ocean atoll islands are perceived as fragile landforms being physically susceptible to climate change, sea level rise and extreme events such as hurricanes and tsunami. The Sumatran tsunami of 26 December 2004 generated waves that reached reef islands in the Maldives 2,500 km away, that were up to 2.5 m high. Here we present observations of the affects of the tsunami, based on pre- and post-tsunami topographic and planform surveys of 13 uninhabited islands in South Maalhosmadulu atoll, central Maldives. In contrast to the devastation along the continental coasts subjected to the tsunami, and also to the infrastructure on inhabited resort, village, capital and utility islands in the Maldives, our surveys show there was no extreme island erosion or significant change in vegetated island area (generally <5%). Instead, the tsunami accentuated predictable seasonal (monsoonal) oscillations in shoreline change promoting localised retreat of exposed island scarps, commonly by up to 6 m; deposition of cuspate spits to leeward; and, vertical island building through overwash deposition, up to 0.3 m thick, of sand and coral clasts covering a maximum 17% of island area. The main erosional and depositional signatures associated with the tsunami were scarping and gullying, and sand sheets and spits respectively. It is believed that these signatures will be ephemeral and not permanent features of the Maldivian islandscape.

INTRODUCTION

The Maldives form a 750 km long archipelago comprising a double chain of 22 atolls that extend from 6°57'N to 0°34'S in the central Indian Ocean (Fig. 1a, b). The archipelago forms the central section of a larger geological structure that stretches from the Lhakshadweep (to the north) to Chagos Islands (in the south). The Maldivian atolls are host to more than 1,200 reef islands that are mid- to late-Holocene in age (Woodroffe 1993; Kench et al., 2005). The islands are small, and rarely reach more than 2-3 m above

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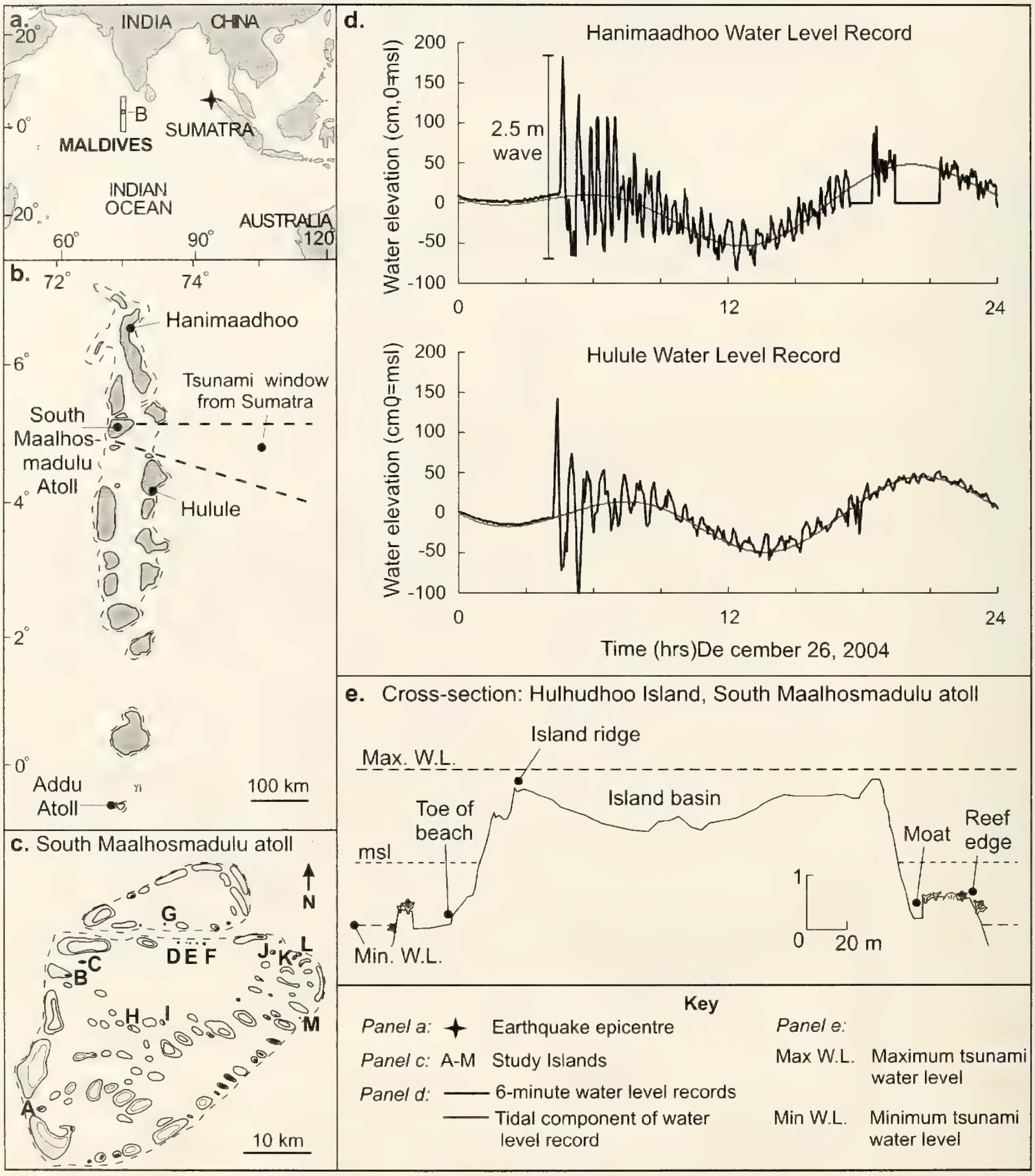

Figure 1. Location of Maldives and South Maalhosmadulu atoll in relation to the epicenter of the Sumatran tsunamigenic earthquake (A-C); Water level records from the northern and central Maldives (D); Surveyed west-east cross-section of Hulhudhoo Island showing maximum and minimum water levels occurring with passage of the first tsunami wave as recorded at the Hanimaadhoo tide gauge (E). Water level records provided by the University of Hawaii Sea Level Center.

sea level. They are made up of unconsolidated calcareous sand and gravel sediments derived from skeletal remains of organisms living on the adjacent reef including coral, coralline algae, foraminifera and molluscs. The Maldivian islands are located in a predominantly storm-free environment with a process regime marked by strong seasonal

reversals in monsoonal conditions from the west (April to November) and northeast (December to March) that govern short-term changes in island shorelines (Kench et al., 2003). Notably, it was during the northeast monsoon that the Boxing Day 2004 tsunami struck the Maldives with tsunami waves also emanating from the east.

In recent years, it has been argued that the combination of their small size, unconsolidated sediments and low elevation means that the Maldives are particularly sensitive to climate change and rising sea level. Indeed, it has been suggested that the future habitability of these islands is in doubt. Not only are the long-term impacts seen as threatening, but also the impact of contemporary extreme natural events such as tropical cyclones and tsunami. Although the Maldivian islands are not located in a tropical cyclone generating area, they are subject to flooding and swell waves from far distant areas (Harangozo, 1992; Kahn et al., 2002) and tsunami, though the impact of tsunami on the Maldives has not been reported previously. For instance, there is no mention of tsunami in Maniku's (1990) comprehensive summary of changes in the topography of the Maldives. In fact, the role of tsunami in the geological development of atoll islands has only been inferred (Vitousek, 1963) and attempts to distinguish between tsunami and storm deposits in reefal areas in general has not been successful (Bourrouilh-Le and Talandier, 1985; Nott, 1997).

This article presents detailed observations on the geomorphic and sediment changes on reef islands in South Maalhosmadulu atoll, Maldives, resulting from the Sumatran tsunami in December 2004. The observations reported here were made six weeks after the tsunami and were compared with our previous surveys of the islands carried out in 2002 and 2003. These earlier surveys examined the Holocene evolution of islands (Kench et al., 2005), the morphological adjustment of islands to seasonal monsoon shifts in wind and wave patterns (Kench and Brander, 2006), and documented the process regime that controls reef island change (Kench et al., 2006).

THE TSUNAMI WAVES IN THE MALDIVES

The tsunami of December 26th 2004 was generated by a magnitude Mw 9.3 earthquake off the northwest coast of Sumatra (Stein and Okal, 2005). The Maldives were in the direct path of the tsunami in its westward propagation across the Indian Ocean. The first tsunami waves reached the Maldives, situated 2,500 km west of Sumatra, 3.5 hours after the earthquake.

Water levels (Fig. 1d) recorded in the northern region of the archipelago (Hanimaadhoo) indicate that the islands were impacted by an initial 2.5 m high wave with water levels reaching 1.8 m above mean sea level (msl). During the following six hours, an additional 5-6 waves, diminishing in height from 1.8 – 1.2 m, impacted the islands at periods of 15-40 minutes. Water levels recorded in the central archipelago (Hulhule) showed a slightly reduced initial wave height of 2.1 m with water levels of 1.6 m above msl (Fig. 1d). Subsequent waves were also much lower than in the north. The highest waves during the tsunami were coincident with a neap high tide and combined with an ambient southerly swell of about 0.75 m resulted in water levels sufficient to inundate islands across the archipelago (Fig. 1e).

Reconstructions of the tsunami wave height across the Indian Ocean show that interaction of the waves with the Maldives archipelago and broad carbonate bank, extracted significant energy from the initial wave, reducing the height by approximately 0.5 m in its propagation westward across the Indian Ocean.

While the tsunami waves were not as large as those that traveled to the continental margins of southeast and south Asia, they nevertheless had catastrophic consequences, particularly on the inhabited islands. Over 80 lives were lost and a further 100,000 people (1/3 of the population) were affected by the tsunami. Fifty-three of 198 inhabited islands suffered severe damage to infrastructure, while several of the worst affected islands were abandoned (UNEP, 2005).

STUDY ATOLL AND ISLANDS

The focus of this study is South Maalhosmadulu atoll (Fig. 1b, c), located in the central zone and western side of the archipelago. Tsunami waves were able to propagate toward the atoll through a 60 km wide window, between two eastern atolls where depths greater than 2000 m are reached (Fig 1 b). The atoll is approximately 40 km long and wide, and has a discontinuous rim characterised by numerous deep passages up to 40 m deep and 4500 m wide. The effective aperture of the atoll rim (proportion of gaps in the reef) is 37% which allowed propagation of tsunami waves through the atoll lagoon. Eye-witness accounts and photographs taken on Kendhoo Island, situated in the north-central part of South Maalhsomadulu, suggest that waves were manifest as quickly rising surges of small, progressive bores lacking the size and power of the tsunami waves that impacted continental shorelines.

South Maalhosmadulu contains 53 islands found on peripheral and lagoon reefs, with most islands concentrated on the east to southeastern side of the atoll (Fig. 1c). Some of the islands were described by Gardiner (1903: 380-386). Kench et al., (2005) have shown the islands are low-lying accumulations of calcareous materials of mid-Holocene age. Here we present results from repeat surveys on thirteen islands located across the atoll. The islands and their reef platforms have differing dimensions and shapes that are mirrored in the islands they contain and which occupy varying proportions of the reef flat (Table 1).

METHOD

In January 2002, a network of benchmarks was established on 13 uninhabited islands on South Maalhosmadulu atoll (Fig. 2). The number of benchmarks on each island was a function of island size and shape, but was generally between four and six, the locations representing the dominant shoreline exposures. Initial cross-shore beach and reef profiles were surveyed by automatic level. Planimetric details of the vegetation edge and toe of beach lines were mapped using global positioning system (GPS) surveys with Trimble ProXL and Trimble Geoexplorer 3 instruments with a mean horizontal positioning error of +/- 1.8 m. A full description of the methodology and subsequent data analysis associated with the GPS surveys is given by Kench and Brander (2006).

Table 1. Physical characteristics of study islands and reefs in South Maalhosmadulu atoll.

Island	[a]Reef Area (m^2)	[b]Island footprint (m^2)	[c]Veg. area (m^2)	Beach area (m^2)	Isld. length (m)	Isld. width (m)	% reef occupied by Island
Gaaviligilli	990,000	23,130	17,701	5,429	336	129	2.4
Fares	3,579,945	125,297	101,585	23,713	691	212	3.5
Dhakandhoo	219,136	62,121	45,041	17,080	499	158	28.4
Keyodhoo	88,796	28,985	21,702	7,283	218	180	32.6
Hulhudhoo	85,512	39,236	30,579	8,657	249	209	45.9
Udoodhoo	222,275	124,340	112,957	11,383	409	403	55.9
Boifushi	132,000	10,447	0	10,447	266	55	7.9
Nabiligaa	189,000	21,822	2,069	19,753	596	61	11.6
Mendhoo	270,000	145,907	130,346	15,561	626	320	54.0
Madhirivadhoo	170,920	57,060	40,083	16,977	339	261	33.4
Milaidhoo	350,322	51,390	36,070	15,320	341	216	14.7
Thiladhoo	217,189	46,547	33,375	13,172	281	220	21.4
Aidhoo	149,620	32,316	23,650	8,666	414	110	21.6

[a]Reef area calculated from aerial photographs. [b]Island footprint refers to both the vegetated stable island and the dynamic outer beach. [c]Vegetated area. Island area values calculated based on January 2002 gps surveys.

The cross-section and planimetric morphological surveys were repeated for a sub-set of eight islands in June 2002 and February 2003 to document seasonal island dynamics in response to changing monsoonal conditions. The findings are described by Kench et al. (2003) and Kench and Brander (2006) and represent a baseline against which tsunami impacts can be quantified and assessed.

Both plan and profile surveys were repeated six weeks after the tsunami in February 2005. All of the original 13 islands were measured to assess potential changes in island area, shape, position and sediment volume in response to the tsunami waves. Additional mapping and surveying of tsunami inundation zones was conducted using both automatic level and GPS. Erosional and depositional imprints of the tsunami were also surveyed with subsurface stratigraphy being observed through trenching and shallow coring.

PLAN AND PROFILE SURVEY RESULTS

Results of plan and profile surveys on each island are summarized in Figures 3-14 and described below, from east to west across the atoll. Changes in vegetated island area and area of island beach footprint are summarized in Table 2 for all islands. Photographs are presented at the end of the text.

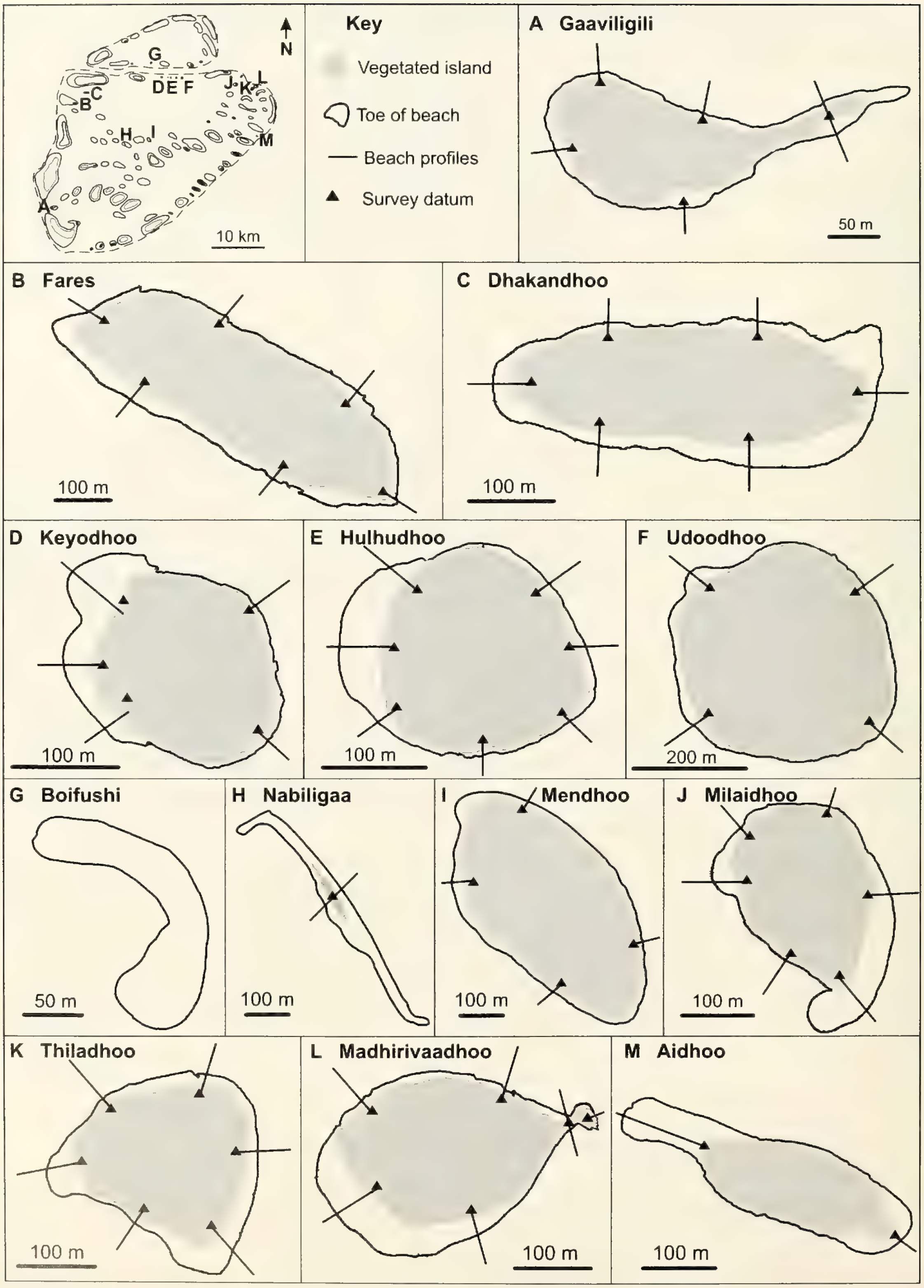

Figure 2. Surveyed islands on South Maalhosmadulu atoll showing vegetated island area and toe of beach line in January 2002 based on GPS surveys, and location of island-beach-reef profiles and benchmarks.

Table 2. Summary and comparison of pre- and post-tsunami surveys of island characteristics in South Maalhosmadulu atoll.

Island	Pre-tsunami surveys				Pre-tsunami dynamics of island beach					Post-tsunami Surveys		Pre- vs post-tsunami changes in reef islands			Tsunami impacts		
	[a]Veg. isld. Area	[b]Beach area			[c]Seas. change	[d]Seas. change	Net change Jan 02 Š Feb 03	[e]Annual change	[f]Mean beach area NE	[a]Veg. isld. Area	Beach area	[g]Beach area	[h]Veg area	[i]Beach expan-sion	Max. Over-wash depth	Area over-wash	Scarped shoreline
	Jan 02 (m^2)	Jan 02 (m^2)	Jun 02 (m^2)	Feb 03 (m^2)	(m^2)	(%)	(m^2)	(%)	(m^2)	(m^2)	(m^2)	(%)	(%)	(m^2)	(m)	(%)	(%)
Aidhoo	23,650	8,666	-	-	-		-	-	8,666	21,521	11,916	37.5	-9.0	5,079	0.10	17.4	21
Madhirivad.	40,083	16,977	18,141	15,620	2,521	± 15	-1,357	-8.0	16,298	36,848	15,572	-4.5	-8.07	2,490	0.20	16.0	54
Thiladhoo	33,375	13,172	14,114	14,885	942	± 7	1,713	13.0	14,029	31,252	15,128	7.8	-6.36	3,163	0.30	17.4	28
Milaidhoo	36,070	15,320	18,619	14,821	3,798	± 25	-499	3.3	15,070	34,087	19,169	27.2	-5.5	3,671	0.30	14.1	40
Udoodhoo	112,957	11,383	18,730	11,163	7,567	± 66	-220	-1.9	11,273	112,867	11,209	-0.6	-0.08	1,550	0.04	9.1	17
Keyodhoo	21,702	7,283	8,408	8,049	1,125	± 15	766	10.5	7,666	21,846	6,195	-19.2	0.67	1,572	0.10	4.7	30
Hulhudhoo	30,579	8,657	10,734	9,975	2,077	± 24	1,318	15.2	9,316	29,521	8,222	4.3	-3.46	1,154	0.13	12.8	31
Boifushi	0	10,447	10,553	10,446	107	± 1	-1.0	-0.01	10,447	0	9,331	-10.7	0	2,482	0.0	100	0
Nabiligaa	2,069	19,753	-	-	-	-	-	-	19,753	536	23,024	17.2	-80.47	9,729	0.10	48.0	23
Mendhoo	130,346	15,561	-	-	-	-	-	-	15,561	129,866	17,754	14.1	-0.37	3,396	0.10	<1.0	0
Dhakandhoo	45,041	17,080	12,875	19,421	6,546	± 38	2,341	13.7	18,251	42,782	20,535	12.5	-5.2	2,915	0.20	7.7	27
Fares	101,585	23,713	19,128	23,114	4,585	± 19	-599	-2.5	23,413	99,746	26,136	11.6	-1.8	1,914	0.10	0.7	24
Gaaviligilli	17,701	5,429	-	-	-	-	-	-	5,429	17,500	6,321	12.7	-1.14	1,609	0.10	10.3	26

[a]Vegetated island area. No significant change was observed between January 2002 and February 2003. [b]Area of beach that extends from the vegetated island ridge and intersects the reef platform. [c]Maximum seasonal changes in beach area. [d]Maximum seasonal fluctuation as percentage of Jan 2002 beach area. [e]Net annual change in beach area. [f]Net annual change as percentage of January 2002 beach area. [g]Change in beach area as percentage of the mean beach area in the NE monsoon from baseline monitoring. [h]Change in vegetated island areas as percentage of the 2002/3 vegetated island area. [i]Area that toe of beach extends beyond both the Jan 2002 and Feb 2003 footprint. All calculations based on GIS analysis of GPS surveys.

Eastern Islands

Aidhoo (Figure 3). Aidhoo, the easternmost of the surveyed islands comprises a sequence of gravel ridges on its eastern margin, whereas the western end of the vegetated island is composed of sand. A sand spit extends lagoonward, towards the northwest for over 150 m across the reef platform. Comparison of pre- and post- tsunami GPS surveys indicates that the vegetated island area was reduced by 9% with most of this reduction occurring along the southern and northern shorelines where erosional scarping was notable (Fig. 3).

Little change was detected in the toe of beach GPS surveys, and in the profiles across the eastern gravel ridge sequence (Fig. 3 b). Note however, that the beach toe retreated a short distance along both the northern and southern flanks of the island. In contrast, the trailing sand spit extended lagoonward both to the north and west toward the edge of the reef platform and beyond the footprint of the beach of earlier surveys. This expansion represents an increase in beach area of about 37% which extends across approximately 5,000 m^2 of reef surface.

Figure 3 also shows that the island surface experienced wave inundation from the tsunami. Overwash sediments consisting of discontinuous veneers of sand together with deposits of coarser coral gravel covered approximately 17% of the vegetated island surface extending from the eastern end of the island along most of the northern shoreline.

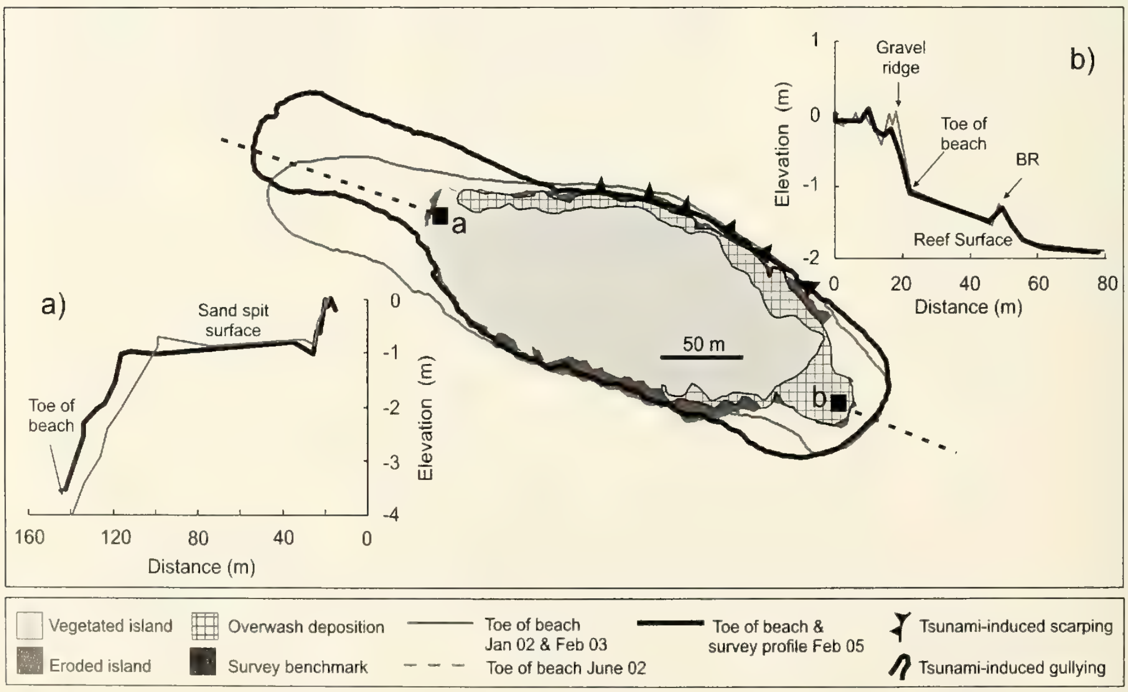

Figure 3. Pre- and post-tsunami plan and profile changes on Aidhoo Island. Location of island shown in Figure 2.

Madhirivadhoo (Figure 4). Mahirivadhoo, the northernmost of the study islands, consists of a small gravel island situated close to the reef edge in the east, and a much larger sand island that occupies the central to southwestern sector of the reef platform. Prior to the tsunami, the two parts of the island were connected by a narrow sand tombolo but during the tsunami the tombolo was breached and a 10 m wide channel separated the two islands when surveyed in February 2005 (Fig. 4, Plate 1). Pre- and post-tsunami GPS surveys record significant erosion along the northern to southeastern shoreline (Fig. 4) which accounted for about an 8% loss in vegetated island area. These sectors, totaling 54% of the shoreline, also exhibited distinct scarping, including root scour that undermined vegetation at the island margin (e.g. Plate 2).

Surveyed cross-sections clearly show both erosional and depositional signatures with shore retreat by up to 6 m (Fig. 4b) and extensive overwash sedimentation covering 16 % of the island (mean depth 0.2 m) primarily on the north to southeastern sections of the island (Fig. 4). Paradoxically, in these same areas the position of the toe of beach had

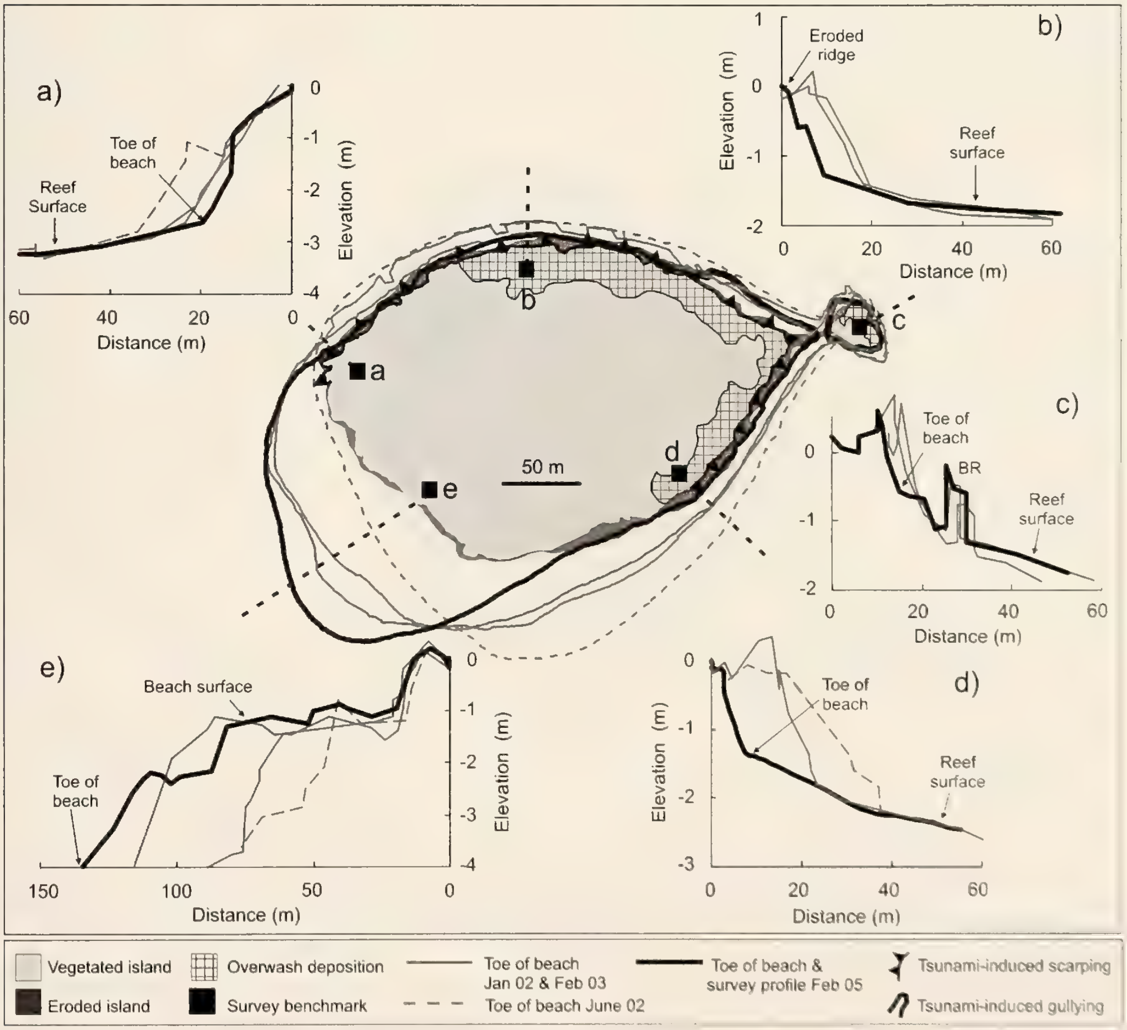

Figure 4. Pre- and post-tsunami plan and profile changes on Madhirivadhoo Island. Location of island shown in Figure 2.

contracted landward of the envelope of positions observed in pre-tsunami surveys, and the total beach area had been reduced by 4.5%. In the southwest of the islandthe response was quite different, the beach toe extending well beyond the positions previously surveyed, by more than 20 m and occupying an additional 2,490 m^2 of reef flat surface (Fig 4 e). Indeed, in the extreme southwest the sand lobe extended to the reef edge and sand was observed cascading off the reef flat down the fore-reef. This was one of the few examples where there was clear evidence of off-reef sediment transport.

Thiladhoo (Figure 5). Thiladhoo is a crudely triangular shaped island with its apex towards the northeast. In this area, and along the western and eastern shorelines, erosion of up to 9 m was measured (Fig. 5 b) with scarping common. In total, erosion accounted for nearly 7 % loss in vegetated island area. In spite of this, tsunami overwash deposition covered a greater area and occupied 17% of the island surface (Fig. 5). Overwash deposition reached its maximum thickness of 0.3 m at the island edge and tapered landward. The toe of beach had contracted landward on the tsunami-exposed eastern flank of the island, with depositional lobes extending towards the south and southwest. These nodes of accumulation were extensive, reaching up to 30 m across the reef surface, and covering an additional 3,160 m^2 of reef surface burying live corals in the process.

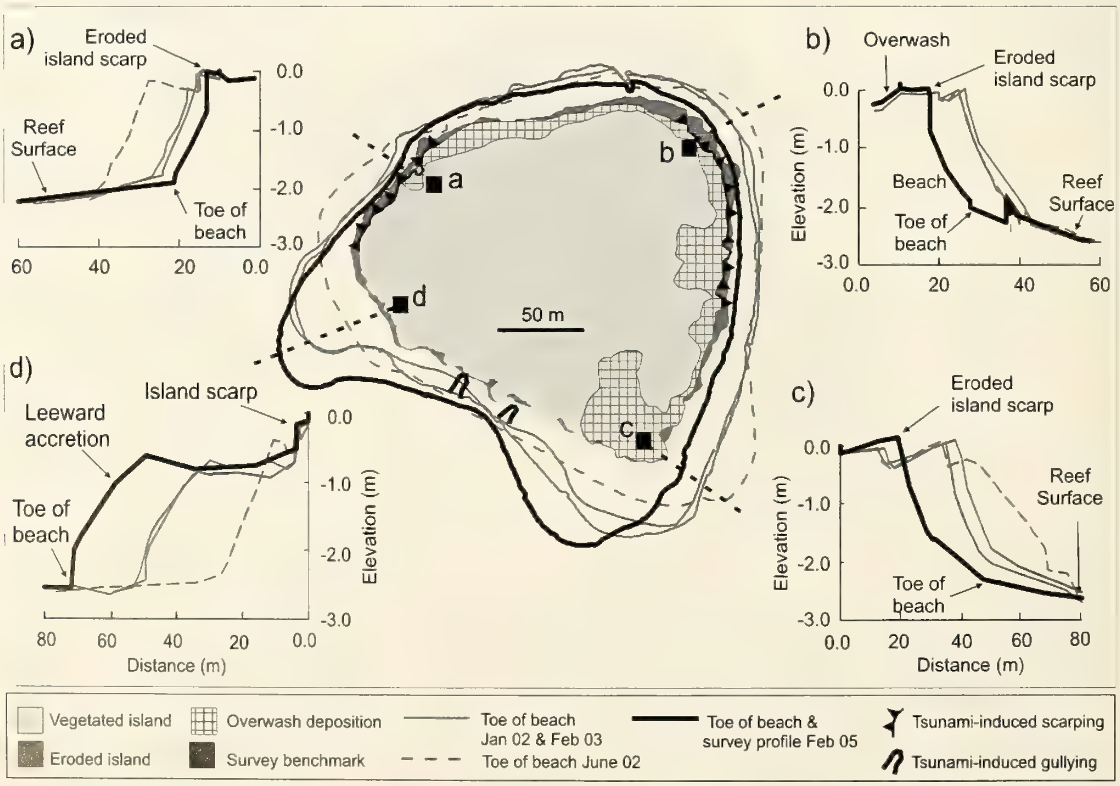

Figure 5. Pre- and post-tsunami plan and profile changes on Thiladhoo Island. Location of island shown in Figure 2.

Milaidhoo (Figure 6). Comparison of GPS surveys indicates that tsunami-induced erosion reduced the vegetated area of Milaidhoo by an estimated 5.5%. Most erosion occurred along the northern shoreline with surveyed cross-sections indicating erosion of up to 4 m (Fig. 6 b). Overwash sedimentation on the vegetated island surface was not common in this area, but was concentrated in the southern half of the island on both eastern and western surfaces. The southeastern overwash sheet was up to 0.3 m thick and it appeared that these sediments originated from the broad sandy beach and berm along the eastern side of the island which had been deposited towards the end of the westerly monsoon season. Further details of the morphostratigraphy and sediments of the tsunami deposits on Milaidhoo are presented later in the section on depositional signatures.

Similar to other eastern islands, the base of the beach was located landward of its pre-tsunami position on the northwestern, northern and southeastern sides of the island (Fig 5 a, b, e) but had expanded as a broad, recurved spit across the reef surface on the southern side of the island occupying a further 3,500 m^2 of reef flat.

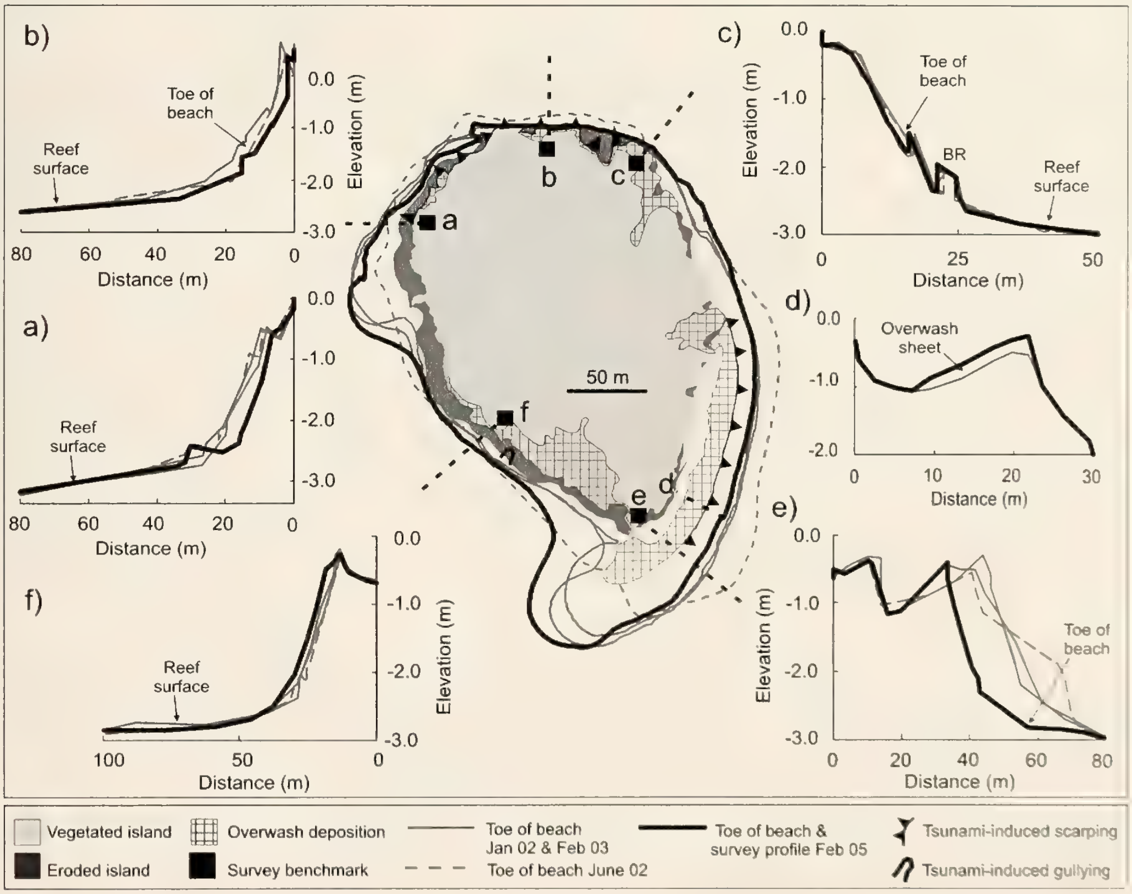

Figure 6. Pre- and post-tsunami plan and profile changes on Milaidhoo Island. Location of island shown in Figure 2.

Central Islands

Udoodhoo (Figure 7). Located in the central north of the atoll, the circular island of Udoodhoo is the second largest island in the study (Table 1) covering over 100,000 m^2 and occupying about 56% of its reef platform. Pre- and post-tsunami survey data indicate Udoodhoo experienced no significant loss in vegetated island area (0.01%). Similarly, the detailed profile surveys show only localized scarping of the island margin notably on the northeast shoreline (Fig. 7 b, c). However, part of the island was overtopped by the tsunami as indicated by a thin sheet (0.04 m) of overwash deposition on the east to southeastern margins which covered about 9% of the total island area (10,239 m^2). On Udoodhoo the toe of beach had marginally contracted landward of the pre-tsunami survey positions along the eastern shoreline and had extended reefward along the western margin of the island.

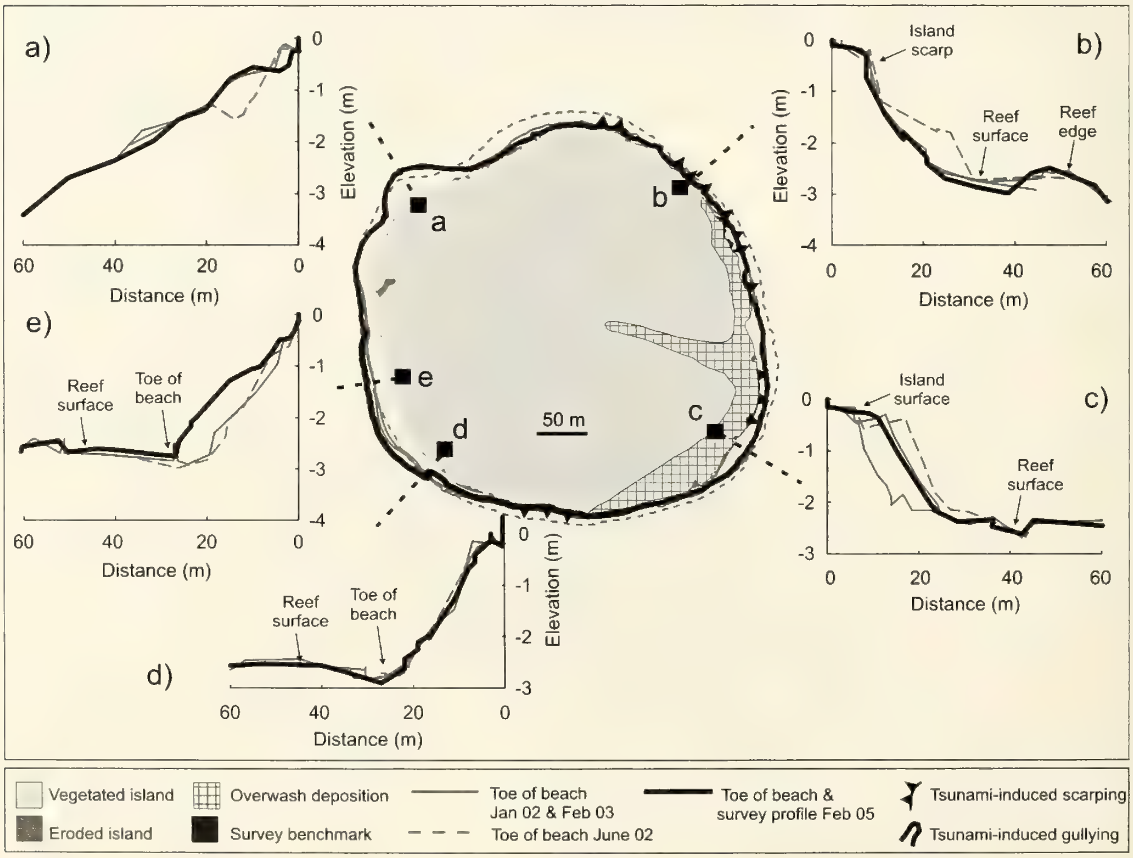

Figure 7. Pre- and post-tsunami plan and profile changes on Udoodhoo Island. Location of island shown in Figure 2.

Hulhudhoo (Figure 8). Hulhudhoo, a smaller but similar circular island to Udoodhoo, experienced erosion on its northern, eastern and southern shoreline though again the total loss of vegetated area was small (approximately 3.5 %). Scarping was evident along the eroded sections with maximum shoreline displacement of approximately 6 m on the southeast section of coast (Fig. 8 d). A large splay of overwash deposition occurred on the northeast section of the island with sediments to a maximum thickness of 0.13 m extending up to 50 m landward of the seaward island ridge. This deposit covered about 13% of the island surface. Elsewhere, there was no evidence of overwash deposition.

Of the six beach profiles around the island, five showed that the toe of beach was displaced landward of its pre-tsunami position by variable amounts, except on the western lee-side of the island where it extended beyond the prior envelope of change and occupied a further 1,154 m^2 of reef flat beyond the inner moat surface (Fig. 8f).

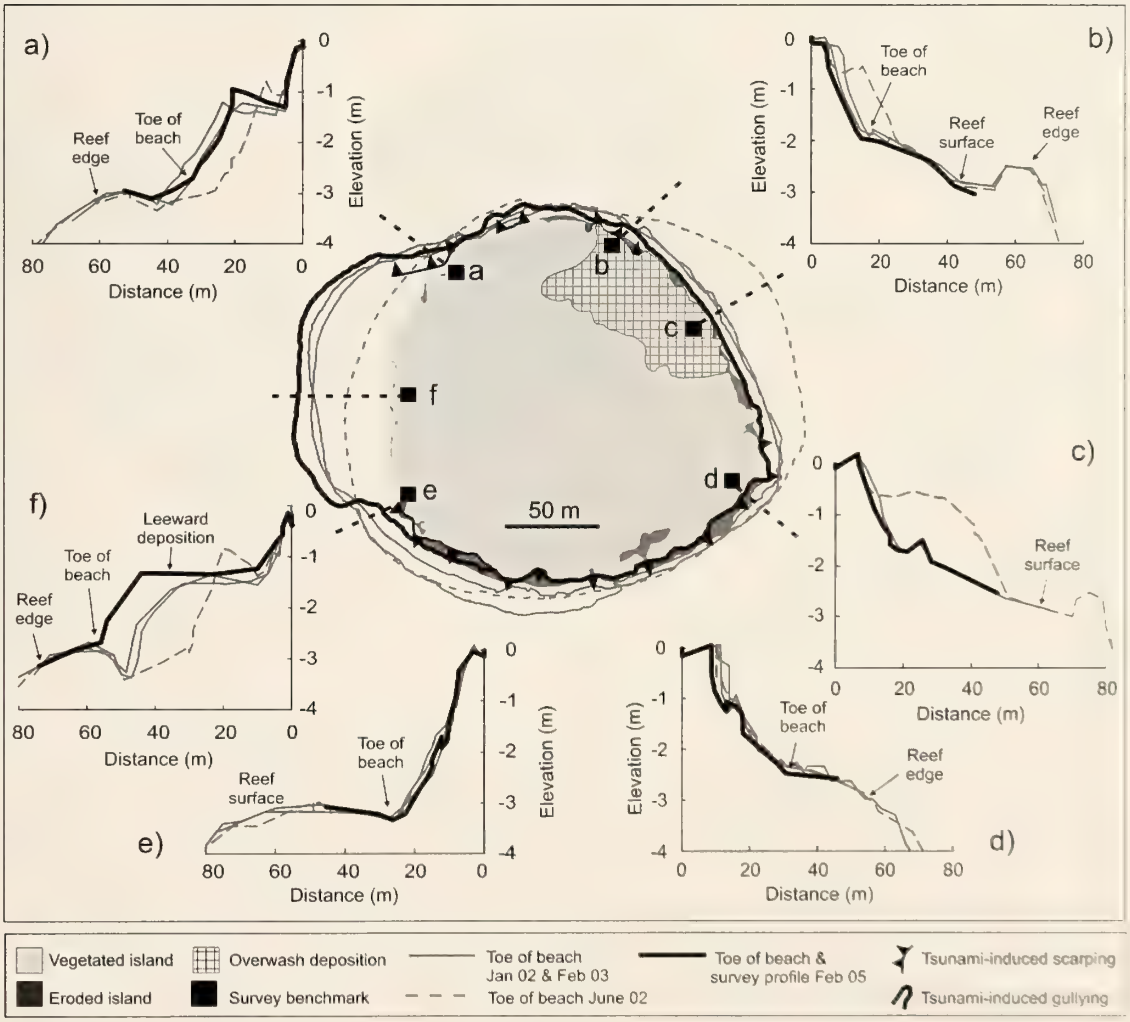

Figure 8. Pre- and post-tsunami plan and profile changes on Hulhudhoo Island. Location of island shown in Figure 2.

Keyodhoo (Figure 9). Keyodhoo is one of the smallest vegetated islands studied and geomorphic changes were similar to those on Hulhudhoo. In particular, marginal erosion occurred on the northern, eastern and southern shorelines with maximum retreat of approximately 6 m in the southeast. Such extensive erosion was, however, quite localized and the total loss of vegetated island area was estimated to be less than 1%. Tsunami-induced overwash deposition on to the vegetated island surface was limited to two locations in the east and covered less than 5% of the island area. However, like Milaidhoo substantial overwash occurred on the broad spit platform located on the protected northwestern side of the island. Toe of beach surveys are consistent with these trends. Landward contraction is indicated on the tsunami exposed eastern and lateral flanks of the island, while to the northwest the beach base had extended further across the reef surface (Fig. 9a), commonly by more than 10 m.

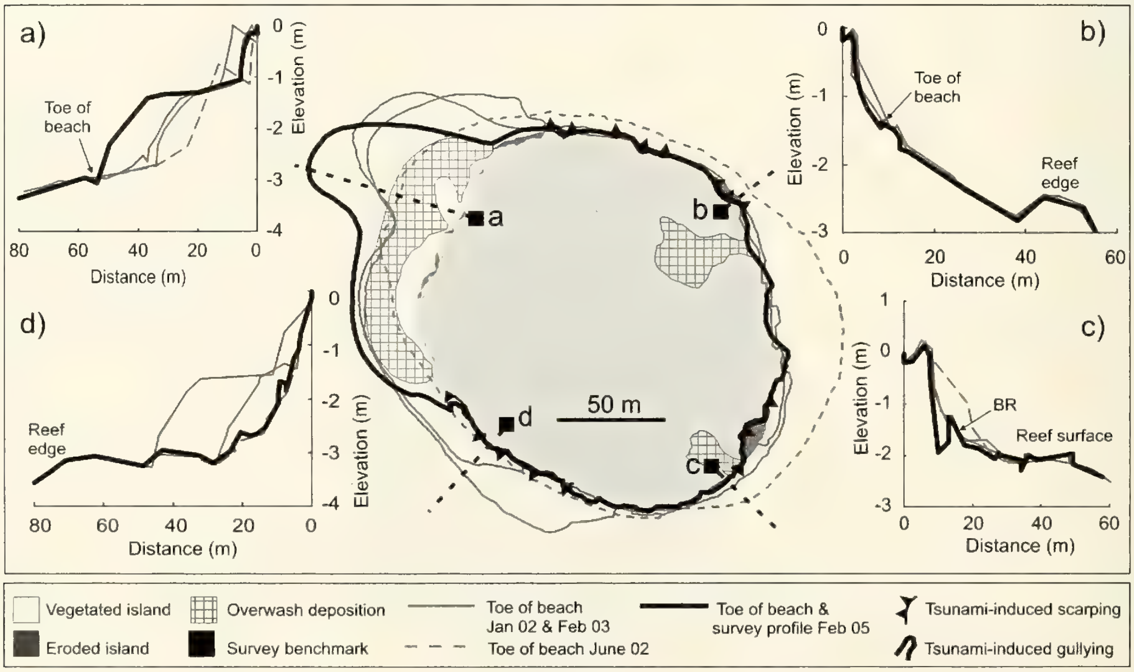

Figure 9. Pre- and post-tsunami plan and profile changes on Keyodhoo Island. Location of island shown in Figure 2

Mendhoo (Figure 10) *and Nabiligaa* (Figure 11). These two islands are located in the centre of the main lagoon of South Maalhosmadulu. Both islands are oriented NW-SE, that is orthogonal to the direction of tsunami propagation. Nabiligaa is elongate, with a long axis of about 500 m and a width of 50 m. It is a sparsely vegetated sand cay, vegetation covering only about 2,000 m^2 in 2002. The island occupies about 12 % of the reef platform. Mendhoo is larger, oval in shape with a long axis of about 700 m and maximum width of 400 m and occupying about 54.5 % of the reef platform. Pre- and post- tsunami GPS surveys were carried out on both islands, but there are no post-tsunami profile surveys. On Mendhoo the GPS surveys show negligible changes in shoreline position. In contrast, evidence indicates that tsunami waves swept across the entire

surface of Nabiligaa and promoted loss of 80% of the island vegetation (approximately 1,600 m^2). The cay footprint (denoted by the toe of beach) increased in area by 17% occupying a further 9,729 m^2 of reef surface compared with pre-tsunami surveys. These changes in island footprint suggest the tsunami wave spread the reservoir of cay sediment across a broader area of reef than identified in earlier surveys. Scarping was measured along one quarter of the western shoreline whereas overwash deposition buried vegetation along the eastern margin of the island, reaching a maximum depth of 0.15 m.

Boifushi (Figure 12). Boifushi was the only unvegetated sand cay included in the study. Observations of the cresent-shaped cay indicate the tsunami waves swept over the surface depositing sediments to the west (Fig. 12). While the total area occupied by the cay footprint was reduced by about 10% the discrete mass had migrated up to 20 m southwestward covering 2,500 m^2 of reef surface that had previously not been covered with cay sediments. However, all of our surveys show that the sand cay is mobile both between seasons and between years and the magnitude of the tsunami-induced movement was not exceptional.

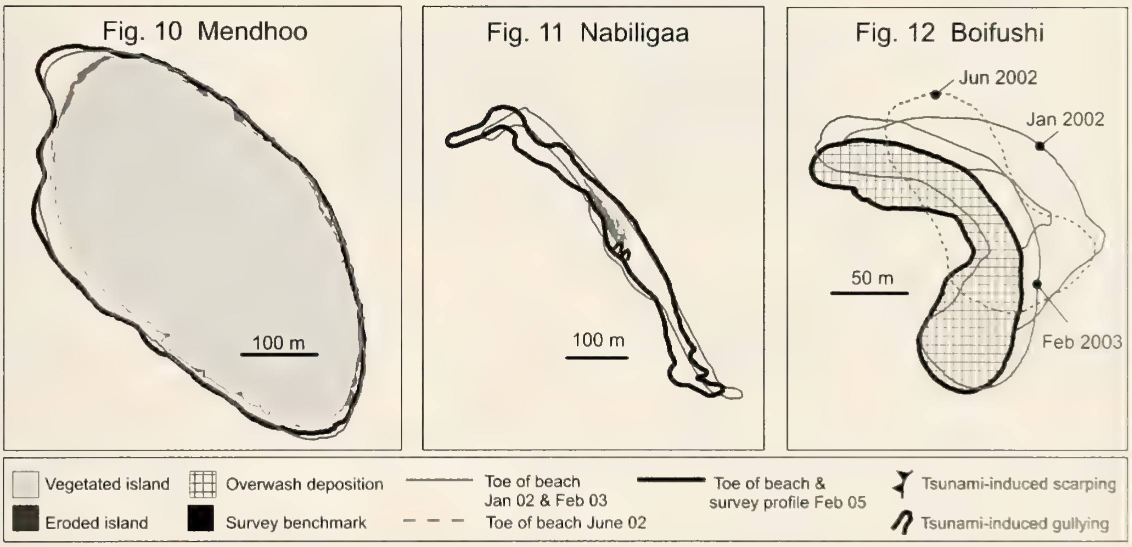

Figure 10-12. Pre- and post-tsunami plan and profile changes on Mendhoo, Nabiligaa and Boifushi Islands. Location of islands shown in Figure 2.

Western Islands

Dhakandhoo (Figure 13). Dhakandhoo is an unusual elongate island in that its long axis is oriented E-W. Erosion was concentrated along the eastern and northwestern shorelines. Prior to the tsunami the eastern end of the island had accreted as a sequence of chevron-shaped ridges and recently colonized by *Scaevola* and *Pemphis* bushes. The tsunami caused significant retreat of this newly accreted area (20 m, Fig 13 d) which provided the greatest contribution to the total loss of vegetated island area of

approximately 5%. On Dhakandhoo, overwash sedimentation was observed at two locations. First, a sand deposit on the northeastern sector of the island, which extended up to 50 m in from the shore, reached a maximum thickness of 0.2 m and accounted for the majority of the 8% of the island surface covered by overwash. The second minor sand deposit occurred on the vegetated berm along the central southern shore.

The toe of beach was situated well landward of the positions surveyed in pre-tsunami surveys on the eastern extremity of the island (Fig 13 d). However, elsewhere the toe of beach was generally seaward of the earlier positions, especially along the southern shore (Fig. 13 e, f). Of note, the total beach area increased by 12.5 % and extended across a further 2,900 m^2 of reef flat surface.

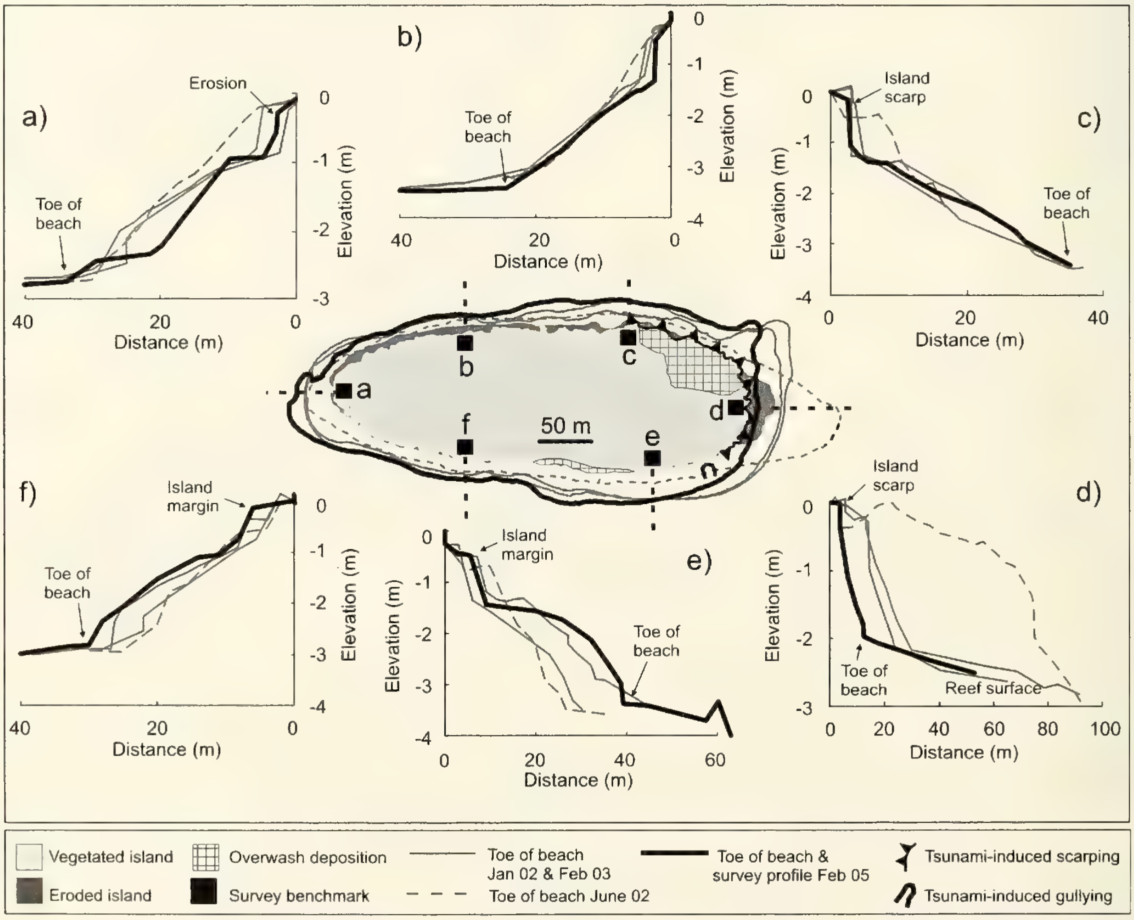

Figure 13. Pre- and post-tsunami plan and profile changes on Dhakandhoo Island. Location of island shown in Figure 2.

Fares (Figure 14). The geomorphic impacts of the tsunami on the elongate island Fares were similar to those on Dhakandhoo. Shoreline erosion and scarping was most evident along the northern and eastern shoreline although the total loss of vegetated area was only 1.8%. Like Dhakandhoo the eastern end of the island experienced significant retreat (15 m, Fig. 14 d). Overwash sedimentation was limited to a small zone on the eastern end of the island and an isolated sand splay on the southern shoreline and affected only 0.7 % of the island surface.

The Fares toe of beach was also located landward of the positions identified in pre-tsunami surveys on the eastern end of the island and showed little change or was further seaward around the remainder of the shoreline (Fig. 14 d, a). Indeed, the beach area increased by 11.6% and occupied a further 1,914 m^2 of reef surface.

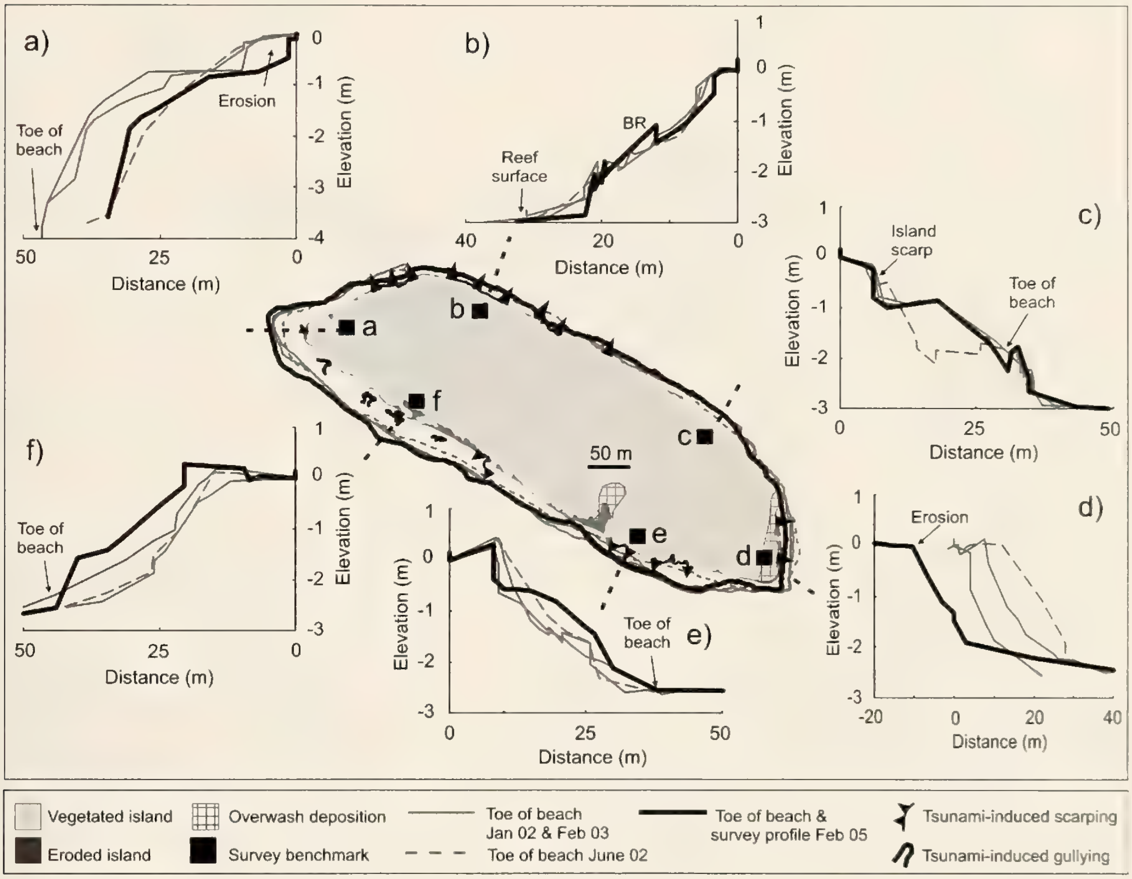

Figure 14. Pre- and post-tsunami plan and profile changes on Fares Island. Location of island shown in Figure 2.

Gaaviligili (Figure 15). Located on the southwestern periphery of the atoll Gaaviligili is composed of gravel at its western margin with a vegetated sand spit that trails across the reef platform toward the ENE and centre of the lagoon. GPS surveys indicate the vegetated island area reduced by 1.14% as a consequence of the tsunami. While marginal trimming of the exposed westward shoreline is evident (Fig. 15 c, d) the gravel ridges experienced minor modifications. In contrast, the eastern one-third of the island, including the sand spit was covered with fresh overwash deposits that in places spilled completely over the island from the northern to southern shore.

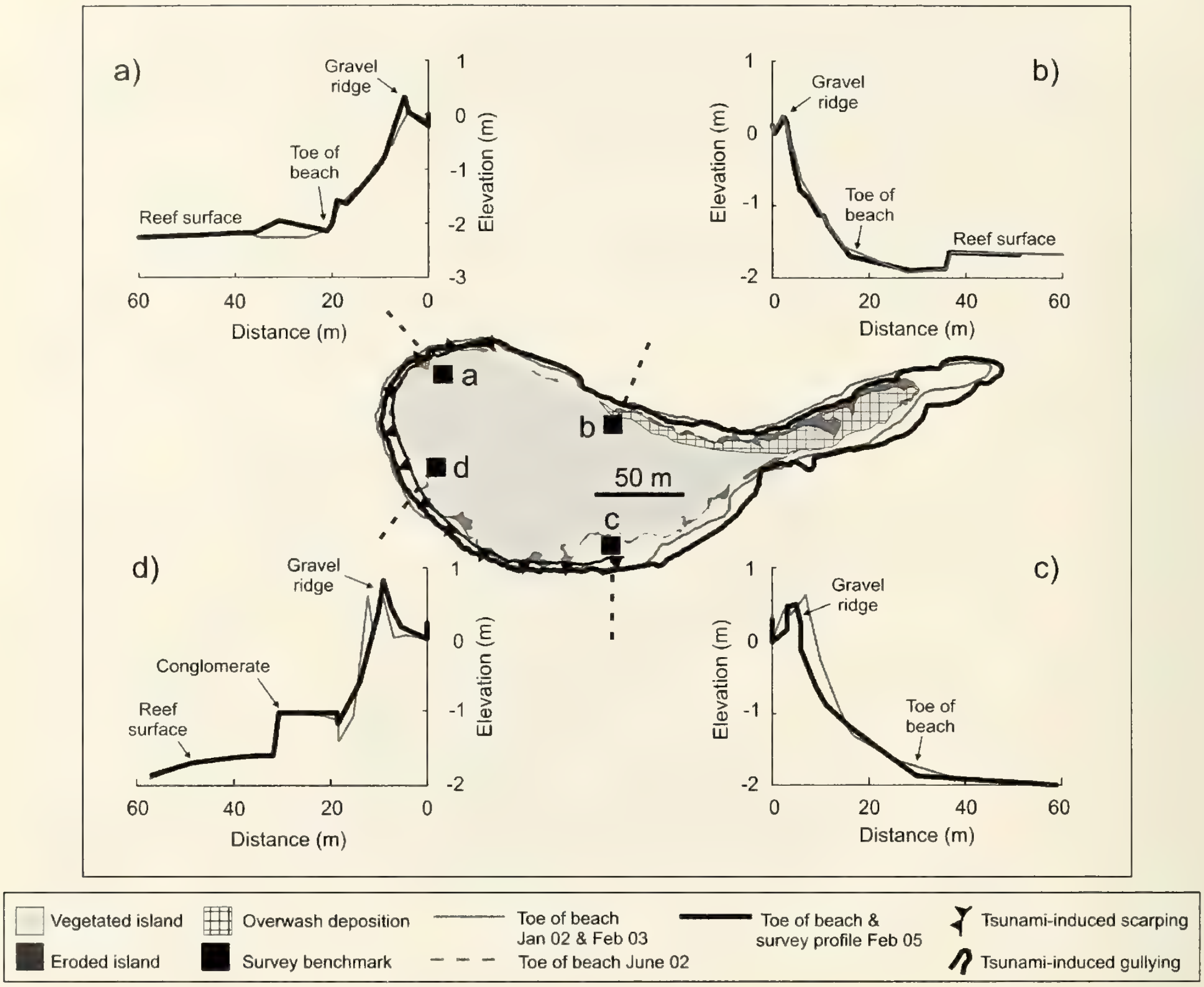

Figure 15. Pre- and post-tsunami plan and profile changes on Gaaviligili Island. Location of island shown in Figure 2.

EROSIONAL AND DEPOSITIONAL SIGNATURES

The changes in island area and beach dimensions described above resulted from tsunami-driven erosional and depositional processes. These processes produced distinctive morphological and sedimentary signatures, which if preserved, can be used as indicators of the incidence of tsunami. During the field survey, observations and measurements were made of both erosional and depositional signatures which are briefly described below.

Erosional Signatures

There were two main forms of tsunami-induced erosion on the study islands: erosional scarps and gullying.

Erosional scarps. The most common evidence of erosion included fresh scarps cut into the vegetated island ridge, exposing root systems and in some cases leading to collapse of trees (Plate 2). On several islands the scarps were impressive features being vertical and up to 2+m high, though more often they were not as high, with a ramp of beach sand and occasionally rubble extending seawards of the scarp marked by a distinct break of slope around the high water mark. While it was obvious that the tsunami had created or freshened up a large number of scarp faces, our data shows that on many islands the scarp at the top of the beach existed before the tsunami, being the product of wave scour during normal monsoonal conditions. The location of pre-existing island scarps varies across the atoll, a pattern that was largely unaltered by the tsunami. Thus, on eastern islands pre-tsunami scarps are generally on the northern and eastern shores while on the elongate islands of the western atoll they occur along western, northwestern and southwestern shorelines. For all islands our post-tsunami surveys record no significant change to the position of these scarps since 2002. However, careful examination of pre- and post-tsunami surveys indicates tsunami-induced scarping did affect up to 54 % of the shorelines on eastern islands, but had relatively little impact on central islands, though fresh scarping also occurred on the exposed eastern tips of the western islands.

Gullying. The second erosional signature of tsunami impact is localised gully scour across the upper beach. In some cases, gullying extends back into the island ridge such as on Fares at the western side of the atoll. Gully dimensions range from 2 - 12 m in cross-shore direction and 2 - 20 m alongshore, with maximum depth of 1.5 m. In all cases the gully headwall is incised into the upper beach, or island ridge with flow indicators (sand splays, exposed roots) recording seaward discharge of water (Plate 3). We interpret these features as evidence for seawater that was ponded in the island basin exiting through low points on the island ridge, and as such represents the only evidence for return flow of tsunami waters. A second process that could have produced gullying is drainage and seepage through the beach foreshore and berm on the receding (drawdown) phase of the tsunami waves. Generally, gullies formed or were preserved most often on the southern and western shores of islands and were best developed where sandy beaches and berms developed seaward of the island vegetation line.

It is possible that more extensive beach gullying may have occurred during the tsunami, but had been infilled by the time of our survey. We consider the long-term preservation potential of these erosional features is poor.

Depositional Signatures

Tsunami deposits on the study islands include localised sand sheets, sand lobes and isolated coral clasts on the island surface, strandlines of coral clasts and rubbish (organic debris & plastic bottles) on the upper beach, and strandlines of rafted debris (coconuts, palm fronds) on island interior basins.

Sand sheets. Localised sand sheets are principally deposited on the northeast to eastern shorelines of islands. They comprise medium to very coarse coral-algal sands

that extend from the island scarp across the landward sloping surface of the island ridge, terminating sharply on the flatter island basin surface (Plate 4) or, more commonly, against dense vegetation. Sand sheet thickness ranges from 0.3 m at the island edge (Plate 5) to <0.01 m up to 60 m landward. The primary sediment source for sand and coral deposits was the beachface with minor contributions from reef flat sediments and reworking of island soil. Where the supply of sand from the beach was sufficient, sand sheets have buried the island scarp forming a continuous deposit from the beach to island surface (Plate 6). Where the sand supply was limited, sand sheets are separated from the island scarp by a bypass zone of non-deposition, typically no wider than 10 m (Plate 7).

Sand sheets on Milaidhoo. Of the 13 study islands, Milaidhoo recorded the most extensive tsunami sand sheet deposit, providing an opportunity to document details of the flow behavior as recorded by sedimentary texture and structure. On the eastern shore of Milaidhoo the tsunami laid down a sand sheet that extends 180 m alongshore, 20 m across-shore and is up to 0.3 m thick.

The sand sheet is a continuous deposit that drapes the former beach face and partially buries vegetation on the backshore (Fig. 16a, Plate 6). Trench excavation of the sand sheet exposed continuous, landward-dipping tabular bedding defined by variations in grain size and composition (Fig. 16a, b, d). Bed thickness ranges from 1 cm to 10 cm, and mean grain size from 0.4 to 0.9 mm. The coarse sand fraction (>0.7 mm) is dominated by whole *Halimeda* flakes and coral fragments. On the surface of the sand sheet, this coarse fraction is deposited as single-grain drapes that in plan view clearly show the run-up limit of wave swash across the sand sheet (Fig. 16c). We interpret these surface drapes as the product of wind-wave action superimposed upon the tsunami-elevated sea surface. The preservation of these drapes is additional evidence that the tsunami did not develop a strong backflow; rather, tsunami waters percolated into the backshore sands and/or drained downslope and alongshore toward the southeast tip of Milaidhoo (Fig. 6). In sum, the well developed tabular bedding and absence of cross-bedding in the trench section suggests that tsunami flow was unidirectional, producing an upper-stage plane bed characterised by pulses of deposition (one pulse per tsunami crest?), with additional flow generated by swash action of wind-waves as tsunami flow waned.

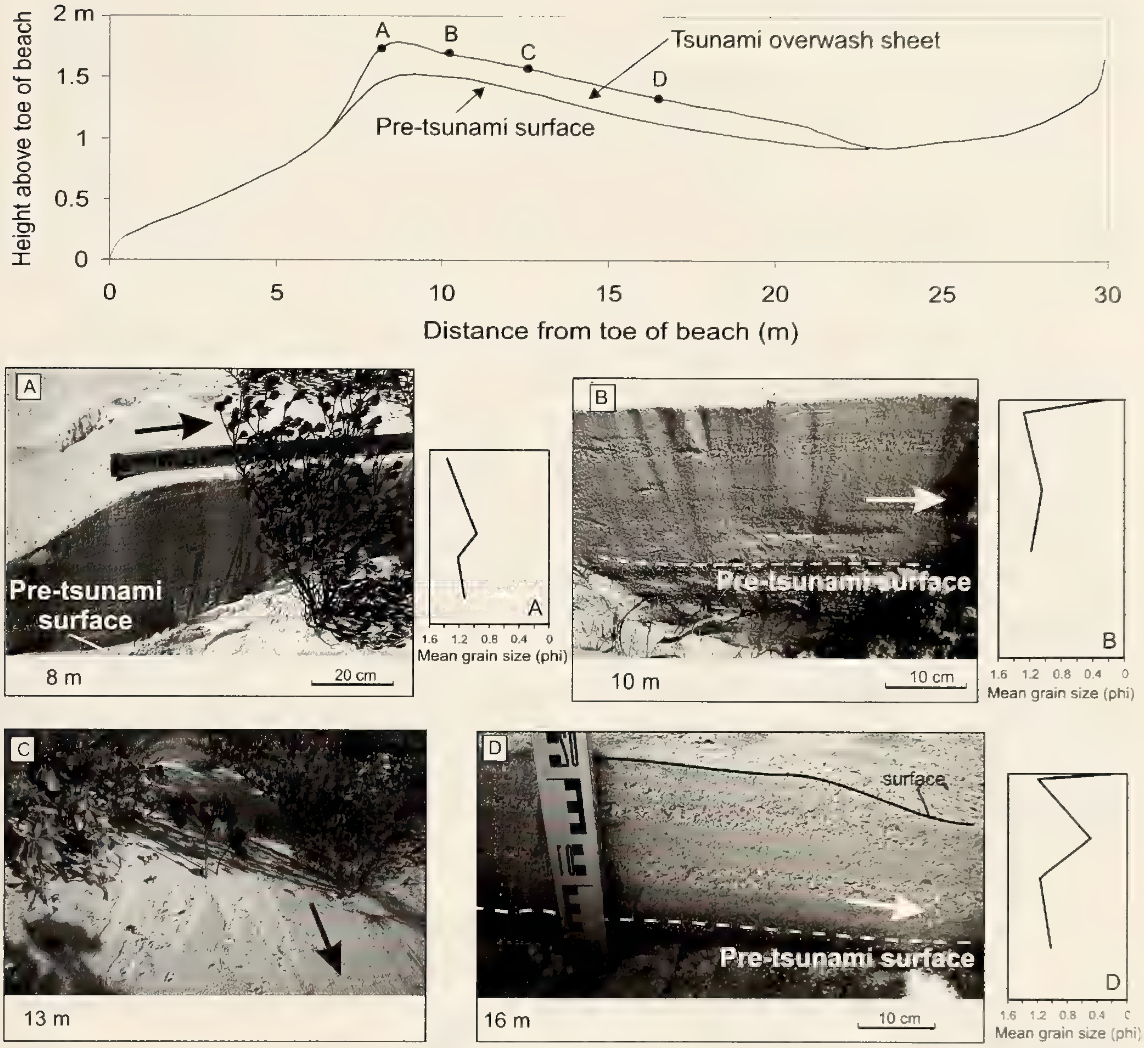

Figure 16. Cross-section profile and trench photos (A, B, D) showing continuous tabular bedding and mean grain size variability of tsunami overwash sheet on Milaidhoo eastern shore. Also showing surface drape of *Halimeda* flakes (C) deposited during waning flow. Arrows indicate direction of tsunami flow.

Sand lobes. Less extensive and more elongate than sand sheets, sand lobes are also commonly convex in cross-section and taper in a landward direction. Isolated sand lobes occurred on several islands. Typically they formed deposits on the island ridge in areas where dense vegetation interrupted tsunami flow, leading to discontinuous sand deposition in the lee of obstacles to a maximum thickness of 10 cm. They also were present at low points around an island's vegetated margin, extending up to 20-30 m inland. Like sand sheets the primary source of sand was the adjacent beach, though in several cases the seaward side edge of the lobe was marked by an erosional scarp.

Coral clasts and vegetative debris. Discontinuous strandlines of coral clasts occurred on island surfaces along the more exposed shores, in places reaching up to 5 m from the vegetation edge or scarp (Plate 8). Isolated coral clasts were deposited across

the island ridge along the trailing shores of islands with respect to the tsunami path. Strandlines of buoyant debris on the upper beach were only preserved on the lee side of islands where tsunami inundation did not cross the island ridge. Together, these forms of depositional evidence only record tsunami run-up, with no evidence for return flow or backwash. This is further evidenced by uprooted and flow-flattened vegetation and stranded rafts of organic debris in the island interior. On some islands, tsunami waters ponded on the island basin leading to forest dieback. On Madhirivaadhoo, for example, water remained ponded in the island interior six weeks after the tsunami.

Beach rock fracture and transport. Beachrock outcrops are exposed on the shorelines of many of the study islands, and at several it was clear that beachrock slabs had been detached and moved further shoreward by the tsunami (Plate 9). The largest slab observed to have been moved was roughly rectangular in shape, and measured around 2 x 1.4 x 0.15 m, and had been transported approximately 3 m up the beach on the northwest coast of Milaidhoo. Detachment and entrainment of beachrock slabs of smaller size was also observed on the southeastern shore of Hulhudhoo, where they were deposited in an imbricated fashion against a pronounced beachrock ledge at about mid-tide level (Plate 10). It would be difficult to distinguish tsunami-transported slabs from those deposited during higher energy storm conditions. The presence of slabs at the foot of the fresh scarp higher on the beach at this site suggests that they were emplaced after the scarp had developed, by one of the later waves in the tsunami event. We found no instances where beachrock slabs had been moved from the foreshore onto the island surface.

DISCUSSION AND CONCLUSIONS

The gross changes in reef island morphology associated with the Sumatran tsunami described here, are primarily the effect of the transfer of beach sediments from the eastern to north eastern end of most islands to the western or southwestern side, with reef islands on the eastern side of the atoll generally experiencing greater erosion than those further to the west. The reductions in island area, which decline from 5.5-9% on the eastern islands of South Maalhosmadulu to 1-5% on the western islands bear out this east-west trend, although the large reduction in vegetated island area recorded at the small elongate island of Nabiligaa (80.5%), in the centre of the atoll, suggests that island size, shape and exposure may also have been important.

The spatial distribution and significance of this sediment transfer is shown on most islands by comparing the position of the toe of the beach at the end of the two previous NE monsoons, with the toe of beach position following the tsunami. On most of the islands surveyed the toe of beach following the tsunami was further west over at least part of the eastern shore than it would normally be at the end of the northeastern monsoon, although we note that for Aidoo and Mendhoo on the eastern atoll rim these effects are not well developed, and at Gaavilgili on the western atoll rim the direction of transfer seems to be dominantly from west to east. These results suggest complex behaviour of the tsunami waves around the atoll rim and within the lagoon. They also

confirm laboratory experiments (Briggs et al., 1995) as well as field observations (Yeh et al., 1994; Minoura et al., 1997) on tsunami run-up around circular islands.

Our data also show that the Sumatran tsunami amplified seasonal movements of the beach from east to west stripping sand from exposed shorelines and transferring it to leeward depocentres. Depletion of sediment in the eastern quadrants exposed these shorelines to prolonged northeast monsoon energy resulting in post-event scarping and extending leeward depocentres beyond the envelope of change in 2002 and 2003. This suggests that had our field surveys been carried out earlier than six weeks after the tsunami, the results would have been subtly different to those that we encountered.

There are three final points that emerge from this study. First, the timing of the tsunami, early in the northeast monsoon, when the beach sand reservoir is positioned on the eastern sides of islands, acted as a buffer to erosion and minimized the direct impact of the tsunami. Second, deposition of sand sheets and sand lobes (<0.3 m thick) on island surfaces is a permanent addition to the islands, increasing elevation and stability. However, the integrity of these tsunami-derived overwash deposits is unlikely to be preserved on the islands we studied due to bioturbation and soil formation. Thus, in contrast to the tsunami imprints described by Dawson and Shi (2000) and Scheffers and Kelletat (2003), recognition of these deposits as tsunami signatures in the geological record is unlikely. Finally, our data show that the uninhabited islands of the Maldives experienced only minor physical impacts from the Sumatran tsunami. This suggests that unmodified atoll islands are robust rather than fragile landforms, which contrasts markedly with the devastating impacts on the modified reefs and inhabited islands elsewhere in the Maldives.

ACKNOWLEDGEMENTS

Pre-tsunami surveys were funded by The Royal Society of New Zealand Marsden Fund, UOA 130 to P.K. We thank the Mohamed Ali and members of the Environment Research Center, Government of Maldives for logistical and practical support in establishment of the pre-tsunami island surveys. Post-tsunami surveys were funded by the Royal Society of New Zealand, The University of Auckland, University of New South Wales and James Cook University, Australia. We thank the Government of the Maldives for permission to undertake post-tsunami surveys.

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Plate 1. Tsunami breach point through former tombolo, northeast tip of Madhirivadhoo. Arrow indicates general tsunami flow direction.

Plate 2. Tsunami-induced scarping and root scour of island margin, northern shoreline of Thilaidhoo.

Plate 3. Water escape channel promoting gullying of upper beach and shoreline, Fares Island. Arrow indicates general flow direction.

Plate 4. Localised sand sheet with abrupt inner limit against low rise on island surface, eastern Dhakandhoo.

Plate 5. Post-tsunami scarping of island margin showing depth of overwash deposition (white band of sediment 0.2 m thick), northern shoreline Thiladhoo.

Plate 6. Localised sand sheet and partially buried vegetation on backshore, eastern Milaidhoo.

Plate 7. Thin sand sheet and sediment bypass zone above pre-existing island scarp, northern Milaidhoo.

Plate 8. Strandline of coral clasts along inner edge of bypass zone, 5 m landward of pre-existing island scarp, northeast Aidhoo.

Plate 9. Freshly exposed beachrock surface where slab marked by arrow has been detached and moved, northern shoreline of Milaidhoo. Beachrock slab is approxinately 1.7 x 1.2 x 0.2 m.

Plate 10. Fractured and imbricated beachrock slabs deposited near the SE point of Hulhudhoo. Slabs to 1.2 x 1.0 x 0.2 m common. Fresh face indicative of fracture and transport during tsunami shown by arrow.

EFFECTS OF THE TSUNAMI IN THE CHAGOS ARCHIPELAGO

BY

CHARLES R. C. SHEPPARD[1]

ABSTRACT

The five atolls and numerous submerged atolls and banks of the Chagos Archipelago are all separated from each other by very deep water, and there are no broad or gently shallowing shelves between the atolls and the site of origin of the December 2004 tsunami. Effects of the recent tsunami in Chagos were mixed. The vegetation of some islands has been damaged in places, but nowhere very extensively. Following an inspection of many islands in all 5 atolls in February 2005, it was clear that the results of the tsunami must be looked at in the context of the shoreline erosion that is taking place in these islands. It appears likely that the tsunami accelerated coastal erosion by 1-2 years on eastern sides at least. Almost all damage seen on land was on eastern sides, where undergrowth vegetation was stripped away in several places, leaving only mature palms.

In the sublittoral, most of these eastern areas had low cover by stony and soft corals, but this was also the case in 1999 and 2001 when coral and soft coral cover was drastically reduced, whose cause was attributed to the 1998 mass mortality. Most areas which now have low benthic cover used to be dominated by soft rather than hard corals; soft corals have shown poor recovery to date in any location in this archipelago. Most western facing seaward reefs previously dominated by stony corals show stronger coral recovery from 1998 than do most eastern facing seaward locations. However, some western facing seaward slopes on Diego Garcia still show very low cover, as was the case in 1999 and 2001. There is no consistent pattern to suggest that the tsunami had any widespread sublittoral impacts, and present coral and soft coral cover appears to be much more strongly determined by the legacy of 1998 and differential recruitment of benthic groups.

Substantial movement of sand was observed on eastern and southern Salomon atoll, and shoreline erosion was marked in many places in all atolls. Refraction around atolls was minimal such that, with one exception, no damage was seen on western sides of atolls.

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INTRODUCTION

The Chagos Archipelago lies just south of the equator in the central Indian Ocean (Fig. 1). It consists of five islanded atolls and at least the same number of awash and submerged atolls and banks, extending over a roughly circular area of diameter >300 km. Its total land area, however, is only about 53 km^2, with another 82 km^2 of reef flats and awash substrate. Of the land area, about half lies in the main island of the southernmost atoll Diego Garcia (2720 ha), which is one of the most enclosed atolls in the world containing deep (>30m) water within its lagoon. One atoll, the Great Chagos Bank, has commonly been described as the world's largest atoll, being approximately 200 km in an East-West direction, though this supports islands only on its western and northern sides. One of its islands, Eagle Island, is the second largest, at 243 ha. Thus the atolls differ markedly in character (Table 1).

Submerged atolls lie around, and in one case between, the islanded atolls. This includes Blenheim, which dries at low tide, and others (e.g. Pitt, Victory, Speakers) whose shallowest surfaces lie variously between 5 and 11 m depth

Bathymetry

Of particular relevance in the present context is the bathymetry of the region. Unlike the Maldives immediately to the north, most of whose atolls lie in a 'double chain' in relatively shallow water, all atolls, submerged atolls and banks in Chagos are separated from others by deep water, mostly 1-2 km deep (see the inset in Figure 1 which shows the 1000 m contours in Chagos). Deep water lies between Chagos and Sumatra (Fig. 2).

Within the archipelago, the proportion of substrate of different depths has been accurately computed (Dumbraveanu and Sheppard 1999) using GIS from all published bathymetric charts of atolls, banks and of the total archipelago. The quantity of substrate estimated is considerably greater than those given in some earlier estimates. While the seaward reefs of each atoll have the classical form of a reef flat at sea level, followed by a gentle slope to a 'drop-off' at about 10-15 m, followed by a steeper slope, there are interesting patterns in the depth distribution of substrate. For example, a simplified extract for depths less than 100 m depth (Fig. 3) reveals a greater proportion of substrate between 20-40 m than 40-70 m depth, and there is another increase of surface area between 70-90 m depth. In these atolls, peak coral diversity lies at 20 m depth, which is deeper than that recorded for most reef systems (Sheppard 1980). This was attributed to the high water clarity and appeared not to be influenced by the location of the drop-off.

Island Erosion

With sea level rising slowly but steadily (Woodworth et al., 2004), and following the warming that occurred in 1998 which caused massive coral mortality in Chagos (Sheppard et al., 2002), the erosion that has been taking place in these shores for many years is accelerating. Elevation transects measured across several islands in these atolls (Sheppard, 2002) show that the centres of many islands lie close to, or even below, high

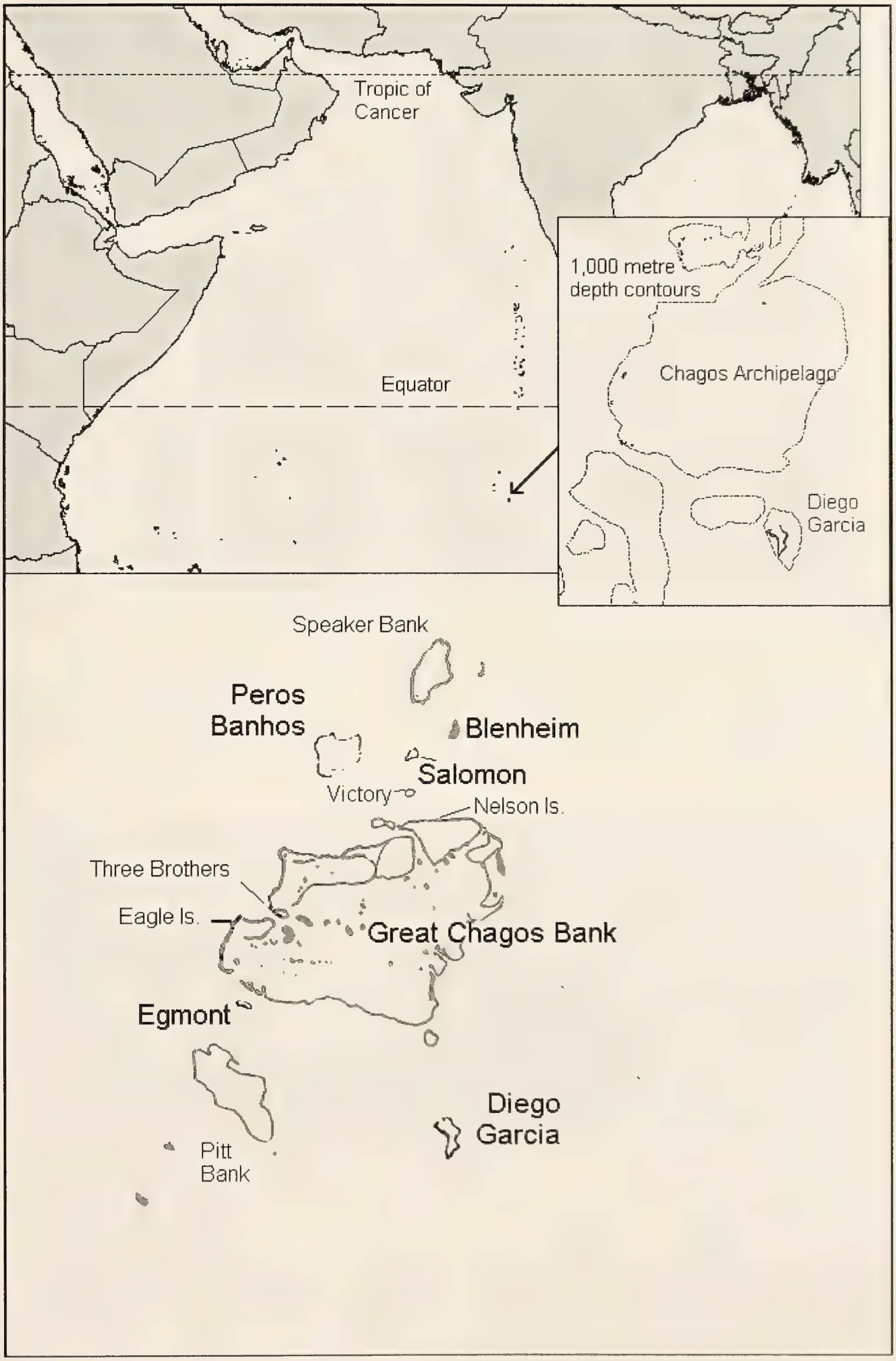

Figure 1. Location map of the Chagos Archipelago.

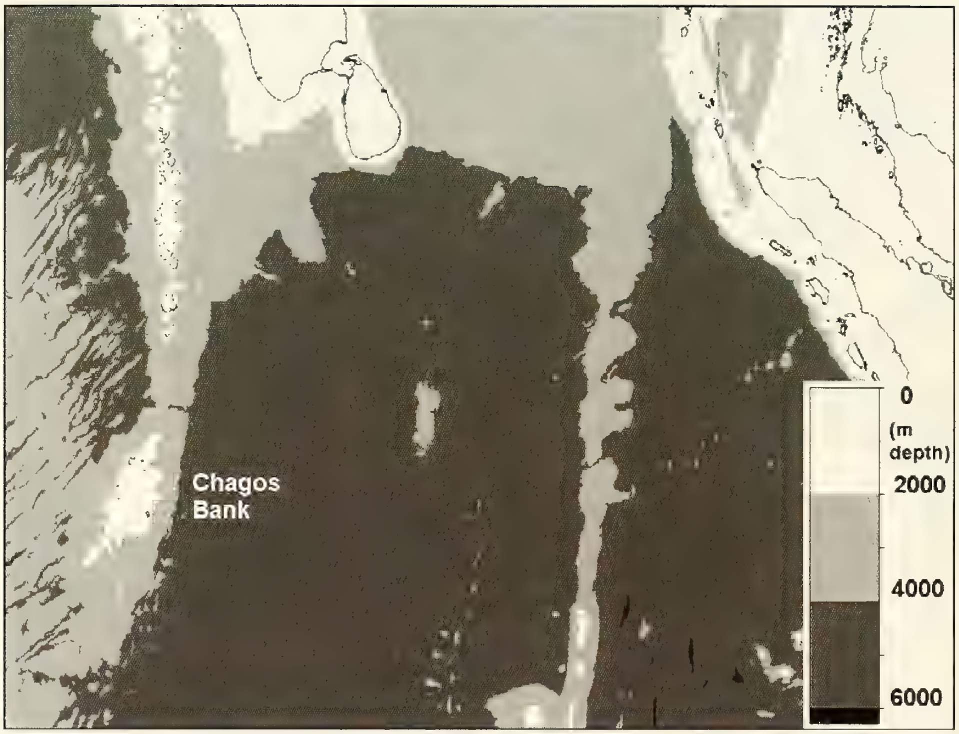

Figure 2. Bathymetry of the Indian Ocean between Chagos and the tsunami site of origin. Taken from GEBCO Digital Atlas (2003). Depth spans are 2000 m depth.

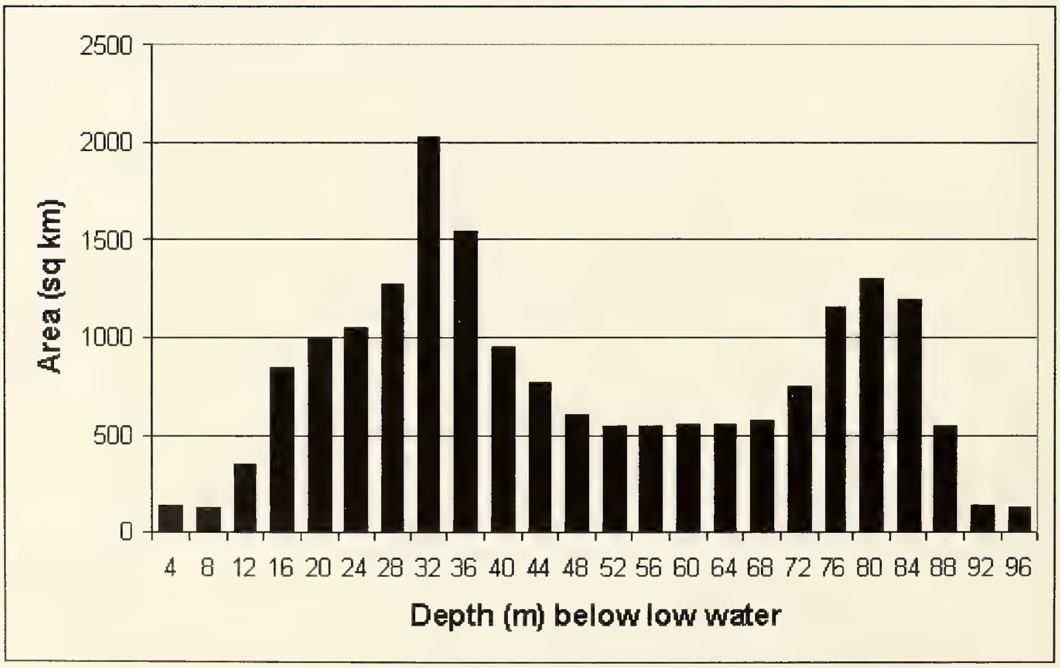

Figure 3. Distribution of areas of different depth spans in the Chagos Archipelago (to 100 m only). On x-axis, each bar indicates the span *to* that depth *from* the shallower depth to its left. From Dumbraveanu and Sheppard (1999).

tide level. They do not usually flood with seawater because each has a raised rim around its perimeter which, quite simply, acts as a dam to water and wave encroachment. That, together with a very high rainfall (Table 1) has been clearly sufficient to maintain persistent fresh water lenses within almost all islands.

Table 1. Areas and physical characteristics of the 5 islanded atolls of Chagos. Rainfall data from Stoddart (1971).

Atoll	Latitude at centre	Atoll area Km^2	Land area (Ha)	No. islands	% rim enclosed by islands	% rim enclosed by islands and reef flats	Max lagoon depth (m)	Raised reef present	Rainfall mm y^{-1}
Peros Banhos	5° 20’	463	953	31	30	65	66	Yes	3 999
Salomon	5° 20’	38	263	11	50	85	30	No	3 751
Great Chagos Bank	6° 10’	18 000	437	8	>2	>5	88	Yes	
Egmont	6° 40’	48	401	3	30	95	17	No	
Diego Garcia	7° 20’	250	2734	5	95	97	32	No	2 599

Erosion is now very evident in many places around many of the islands, and while this has continued progressively for many years it appears to have been accelerating over the last 8 years (scientific visits recommenced in 1996 after a gap of 17 years). Around much of the northern tip of Diego Garcia the erosion is striking; substantial shore defence has been put in place to stop further attrition (Fig. 4).

Figure 4. Northern tip of western Diego Garcia showing concrete armouring against erosion. The reef flat at this site is over 100 m wide. View looking North.

Further south, where a recreational club existed on the western side, there were steps leading down to the beach; now that shoreline is well eroded and the steps have disintegrated. By early 2006, most of the sand had disappeared from large stretches, exposing the underlying limestone. Further south still, the protective rim is now only about a metre wide in places and already some small plumes of beach sand are being pumped through onto the road at high tides (Fig.5).

Figure 5. Erosion of the seaward side of the western arm of Diego Garcia. The observer is standing on the high tide level, the thin rim behind him is now all that stops inundation of the road at this point.

On other atolls there are no fixed structures against which erosion has been measured, but familiarity with several locations shows similar patterns. Therefore, erosion by the sea has been a continuing and accelerating process, one which is not caused only by storms and tsunamis but by every high tide, especially spring tides. The process is being forced faster by rising sea levels. The present brief survey results must be considered against this background.

RESULTS

Direct Damage on Islands

Reports by residents on the day of the tsunami are largely limited to their observations of several large 'tidal cycles' occurring in the lagoon of Diego Garcia during the course of the morning, and of considerable terrestrial debris (palm fronds etc.) being transported along the shorelines. The residents are all located on the western and

therefore sheltered arm of Diego Garcia atoll, and apparently there were no observed instances of damage in that region. Some visitors on yachts anchored in Salomon lagoon further north reported similar unusual tidal movements and swirling of water, but no serious consequences.

The islands were visited in February 2005. Observations of spectacular damage were few. On Diego Garcia's eastern arm, large waves clearly smashed through the vegetation along a section of a few hundred metres, but north and south of that there is no evidence of damage. Where the wave did cross the reef flat and shoreline, the results were removal of all shoreline shrubs (mainly *Scaevola* but with some *Argusia*) and of all young and intermediate-size palms for up to 50 metres inland, but most fully grown trees survived, leaving an untypical vista of palm canopy without undergrowth and a clear view all around. Early visitors to this site reported the presence of a dead shark well inland, as well as some turtles (still alive and thus rescued).

Working northwards through the islands: on Eagle island on the Great Chagos Bank, on the north-eastern shore, there was a remarkable section of several hundred metres where the waves clearly punched 80 - 100 metres inland, stripping away the *Scaevola* bushes and young palms (Fig. 6) removing much of the previously gently sloping beach and leaving a 'step' of 1.5 m high (Fig. 7). When visited two months later, this area had no undergrowth (Fig. 8), but under the canopy of mature palms there were numerous newly sprouting coconuts. This shoreline damage, uniquely in this archipelago, continued around the northern tip and down the north-western facing side for some hundreds of metres too, illustrating the complicated refraction patterns of the waves.On North Brother, the little landing beach has been drastically changed and enlarged (Fig. 9) and the rim is now more narrow than previously. The entire eastern half of this island was clearly affected. The ground nesting Brown Booby colony which has been observed there since at least 1975 was almost certainly washed over, but the colony as a whole has survived. There were no young boobies or chicks in February

Figure 6. Section of the coast of NE Eagle Island where shoreline shrubs and 'undergrowth' have been removed by the tsunami. Breaking water marks the edge of the reef flat. This side of Eagle Island faces East, into the huge lagoon of the Great Chagos Bank.

Figure 7. Observer providing scale to the 1.5 m step formed from eroded and undercut land, at the same site as Figure 6.

Figure 8. East Eagle Island where all undergrowth was removed, including young palms and *Scaevola*. The ground vegetation here (2 months later) is only of newly sprouted coconuts. This is the same site as Figure 6. The affected section of Diego Garcia has an identical appearance.

Figure 9. North Brother's thinning rim near the landing beach, facing approximately east. Shoreline shrubs are missing.

2005, only mature, fully fledged adults and eggs, meaning that there was a gap in the usual demographic pattern, as at that time of year many chicks and young would have been expected too. The western side of the island was still filled with burrows of shearwaters, many occupied.

Middle Brother was packed with uncounted numbers of terns including young and fledglings, and although there was an indefinable change to the shoreline in the area where it is possible to land, this island appeared to be unaffected. The tiny Resurgent island obviously did not suffer a washover despite its small size and exposed location: it had retained its small but healthy colony of adult masked boobies, with young adults and chicks as well as eggs. South Brother had areas of its shoreline shrubs removed in its south-eastern end in manner similar to elsewhere. Nelson island was unaffected and remained packed with birds.

In Salomon atoll, observations of all shores and a walk around Ile Boddam showed substantial erosion of the seaward shores with 'steps' everywhere of 1-2 m high. Yacht-based visitors reported that several turtle nests on these shores had their eggs exposed, to be eaten by hermit crabs and, presumably, by the rats. Sand banks were shifted, and much sand was pumped into the lagoon. Sand shifts around these islands seasonally, and it appears that the result of the tsunami was an acceleration and exaggeration of this process. In Salomon there were no areas of stripped vegetation.

The degree of erosion is impossible to accurately assess given that there were no fixed markers against which to measure change. The North end of Ile de Coin, however, was examined in a little more detail in the late 1970s. The fact that erosion there is proceeding markedly has been remarked on and illustrated well before the tsunami (Sheppard 2002). The changes seen this time, three years after that last visit, have accelerated considerably. The rim of the island there now appears reduced, and appears to have gone completely in places; sand and vegetation form the outer edge of the island at this point. That erosion is increasing here is obvious, but it can only be guessed how much of that is due to the tsunami and how much to the many storms and high tides since the previous visit three years ago.

Sites in these atolls not mentioned above appeared not to have been affected to a noticeable degree.

Sublittoral Observations

In the sublittoral, the reefs were inspected by snorkelling at all the above sites, as well as on east and west sides of Diego Garcia and Salomon atolls, and on the east side of Eagle Island (Great Chagos Bank), West Peros Banhos and in North-East Egmont. The results must be set against the observation, noted above, that coral mortality was very heavy following the 1998 warming, when over 90% of corals were killed to at least 10 and sometimes 30 m deep (Sheppard, 1999). Broadly, while western facing sites which had shown some recovery in 2002 showed much more recovery in 2005 (Fig. 10), those eastern facing sites which had shown almost no recovery in 2002 still showed little recovery.

Figure 10. Underwater off Salomon atoll's Ile Anglais, located on the western side of the atoll, facing West, at the drop-off at 8 m depth. This seaward reef shows young and vigorous growth of table corals.

This pattern was not universal, however: the side of Nelson Island facing Sumatra was seen to be recovering well with good cover of tabular *Acropora* corals (Fig. 11), and similarly, the eastern side of Eagle island off the section where vegetation was stripped away, coral recovery was modest, but included many branching species which remained undamaged (Fig. 12). In eastern Diego Garcia, considerable coral rubble was seen in some eastern seaward locations, but not in others. In all sites, the limited recovery of coral cover that had occurred included healthy colonies of relatively fragile species.

While it might be tempting to conclude that the very low coral cover on eastern

Figure 11. North-eastern end of Nelson Island, Great Chagos Bank, showing young and vigorous growth of table corals. The drop-off here is 6 m depth.

sides could be attributable to tsunami damage, the fact remains that these same sites showed limited or no recovery from the 1998 mortality in 2002 either. Thus caution in interpretation is needed. Another important point is that the eastern sides, exposed to the Southeast Trades, used to be (in 1996) dominated more by soft corals than by hard corals, and the soft coral assemblages at that time were distributable along a 'stress gradient', such that the south-eastern slope of Salomon visited here supported "Rich *Sinularia* & *Lobophytum* coverage on upper slope" in 1996 (see Reinicke and Van Ofwegen, 1999). While recovery in some areas has been strong with respect to hard corals, soft coral recovery has been extremely poor everywhere in Chagos that has been examined to date. For unexplained reasons, soft coral recruitment has lagged well behind that of stony corals. The possibility exists therefore that it is this widespread lack of soft coral recovery in sites which had been dominated by them before 1998, that causes eastern

Figure 12. Eagle Island, eastern or lagoon-facing slope, 7 m depth, offshore from the most heavily affected shoreline. This site is located beneath where Figure 6 was taken. Much of this substrate is covered with *Heliopora*.

sites to remain depauperate compared with western sites. The present information cannot resolve this question. This has been examined more during early 2006, though results are not yet available.

DISCUSSION

These atolls, like many areas in the Maldives, were not impacted nearly as badly as many continental locations. Where there were effects, such as stripped vegetation, this may be due to undefined local bathymetric or funnelling effects, but nowhere did the damage caused by this extend over more than a few hundred metres of shoreline. Numerous reasons have been posted on the internet about supposed effects in Chagos and in Diego Garcia in particular, ranging from the timely raising of submerged barriers to protect the infrastructure on Diego Garcia, to the assertion that the islands were, in fact, lost completely but that this was being kept secret for military reasons. The truth, as described above, is perhaps less interesting. One serious suggestion with more widespread currency is that protection came from the existence of a deeper water ‘trench’ just east of the archipelago. However, although there is a deeper ‘trench’ just East of the Chagos Bank, its depth and extent appear to be no greater than many other irregular

features of the eastern Indian Ocean when that region's bathymetry is examined on a broader scale (GEBCO Digital Atlas, 2000, and see Figure 2). Whether depth effects below 2 000 or 3 000 m are important in connection with tsunami energy is not known to this author.

Underwater, the situation is more interesting and remains unresolved. There is less recovery on most eastern facing seaward reefs, but only where these reefs previously were dominated by soft corals killed in 1998. The few sites examined which had substantial stony coral cover in 1996, now supported substantial cover of the same groups of stony corals (up to 40% coral cover in places). This was conspicuous because the dominant stony corals concerned were usually table *Acropora* species. Areas made more or less bare in 1998 which had been more dominated by soft corals remained more or less bare, given the curious lack of soft coral recruitment. Equally interesting is that there is a strong conservatism in the kinds of corals which were recruiting: where once table corals had dominated but been killed in 1998, leaving much bare substrate for several years, the same species were again emerging in strength. Thus although this has greatly confounded any distinction between tsunami effects and selective recruitment patterns, on balance it seems likely that localised differences in proportions of successful stony corals and unsuccessful soft corals is the likeliest explanation of remaining bare areas of sublittoral substrate in this archipelago.

ACKNOWLEDGEMENTS

This visit was made possible by the staff of the British Party on Diego Garcia and of the Fisheries Protection Vessel *Pacific Marlin*, led by Chris Davies and Bob Goodwin, whose help and hard work made the visit a success. I would mention in particular Paul Maynard, Lee Morrison and Nick Mynard, who assisted with my inspections of many miles of shore and many of the reefs, and Nestor Guzman who assisted me in Diego Garcia. My grateful thanks to them all.

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TSUNAMI IMPACTS IN THE REPUBLIC OF SEYCHELLES, WESTERN INDIAN OCEAN

BY

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ABSTRACT

Temporal and spatial characteristics of the December 2004 tsunami in the Republic of Seychelles, Western Indian Ocean are described, with particular reference to the detailed water level record from the Pointe La Rue tide-gauge, Mahé, and tsunami run-up characteristics on Mahé and Praslin. Assessments of tsunami impacts on coastal and shallow marine environments in the granitic islands of the Northern Seychelles, and on the coral islands of selected locations in the Southern Seychelles, are reported. The lack of noticeable impacts within the southern islands compared to those further north appears to be related to both reduced tsunami wave heights to the south and to differences in regional bathymetry, the tsunami being accentuated by the shelf seas of the Seychelles Bank in the north and not amplified around the southern islands surrounded by deep water.

INTRODUCTION

At some 5000 km from Sumatra, the 115 islands of the Republic of the Seychelles were not in the front line of tsunami impacts. Only two tsunami-related fatalities were reported. Nevertheless, the tsunami did have a considerable infrastructural and economic impact, notably on the northern granitic islands. There was prolonged flooding of the capital, Victoria, as a result of the blocking of the storm drainage system by sediments mobilized by the tsunami, fissuring and failure of dock walls at Port Victoria from repeated inundation and drawdown cycles on unconsolidated fills (Plates 1, 2), washouts of key transport routes by the drainage of tsunami waters from coastal lagoons (Plates 3, 4), disruptions to water supply and sewerage networks (with in the case of the latter attendant pollution problems) and extensive structural damage to houses, hotels, restaurants and other beach-front infrastructure. Total estimates of damage have been assessed at US$30 million (UNEP, 2005) due to both structural damage and loss of earnings following the event. The tsunami was said to have damaged 94 fishing boats, a third of the entire fishing fleet, around Mahé and fish catches for January 2005 dropped

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by 30% compared to previous catches for this month (Payet, 2005, pers. comm.). Here we document the temporal and spatial characteristics of the tsunami in the Seychelles and review its impact on geomorphology and shallow marine ecosystems. We draw heavily on the Canadian United Nations Educational, Scientific and Cultural Organization (UNESCO) mission to the Seychelles (Jackson et al., 2005) and on the International Union for the Conservation for Nature and Natural Resources (IUCN) report (Obura and Abdulla, 2005), supplemented by our own observations in Mahé (Stoddart and Hagan, 1 and 4/2005) and the remote southern islands of the Amirantes, Alphonse/St. François and Providence Bank (Hagan, 1/2005), Aldabra and Assumption (Stoddart 4/2005).

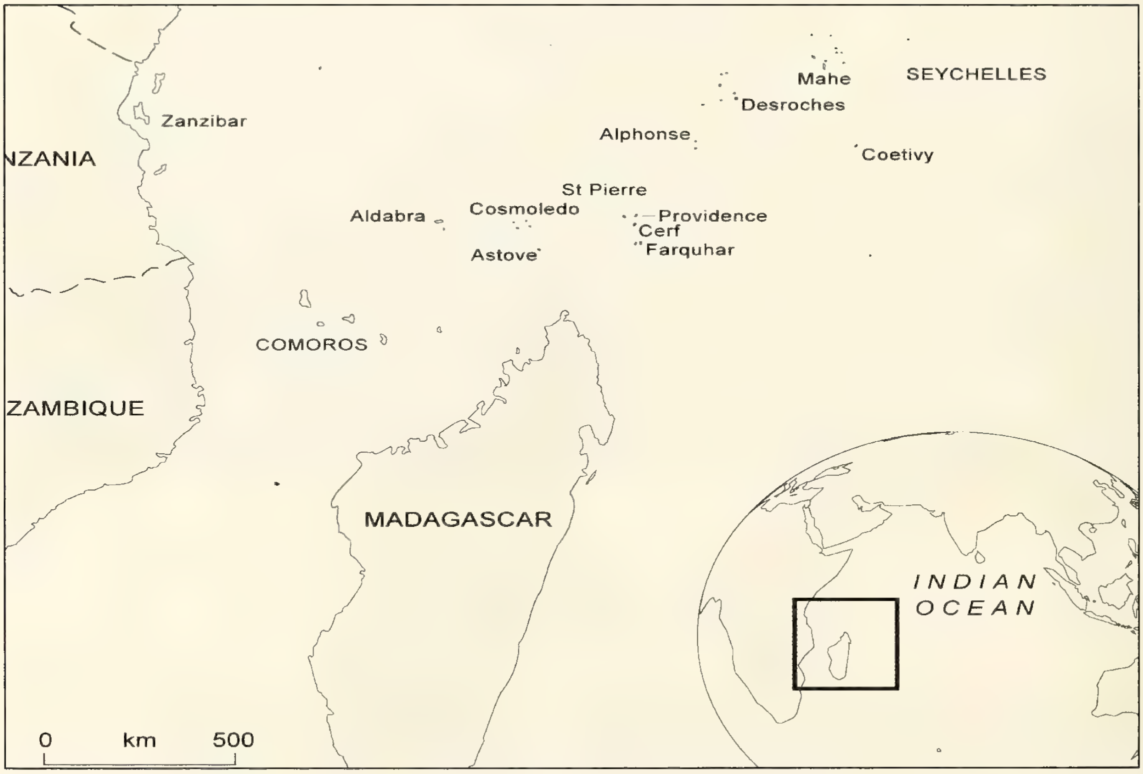

Figure 1. Islands of the Seychelles, western Indian Ocean (after Stoddart, 1970).

CHARACTERISTICS OF THE 26 DECEMBER 2004 TSUNAMI IN THE SEYCHELLES

Temporal Characteristics: Granitic Islands of the Northern Seychelles

Tsunami waves reached the Seychelles at about the same time they impacted Mauritius and Salalah, Oman, ca. 7 hours after the earthquake (Fig. 2; Merrifield et al., 2005).

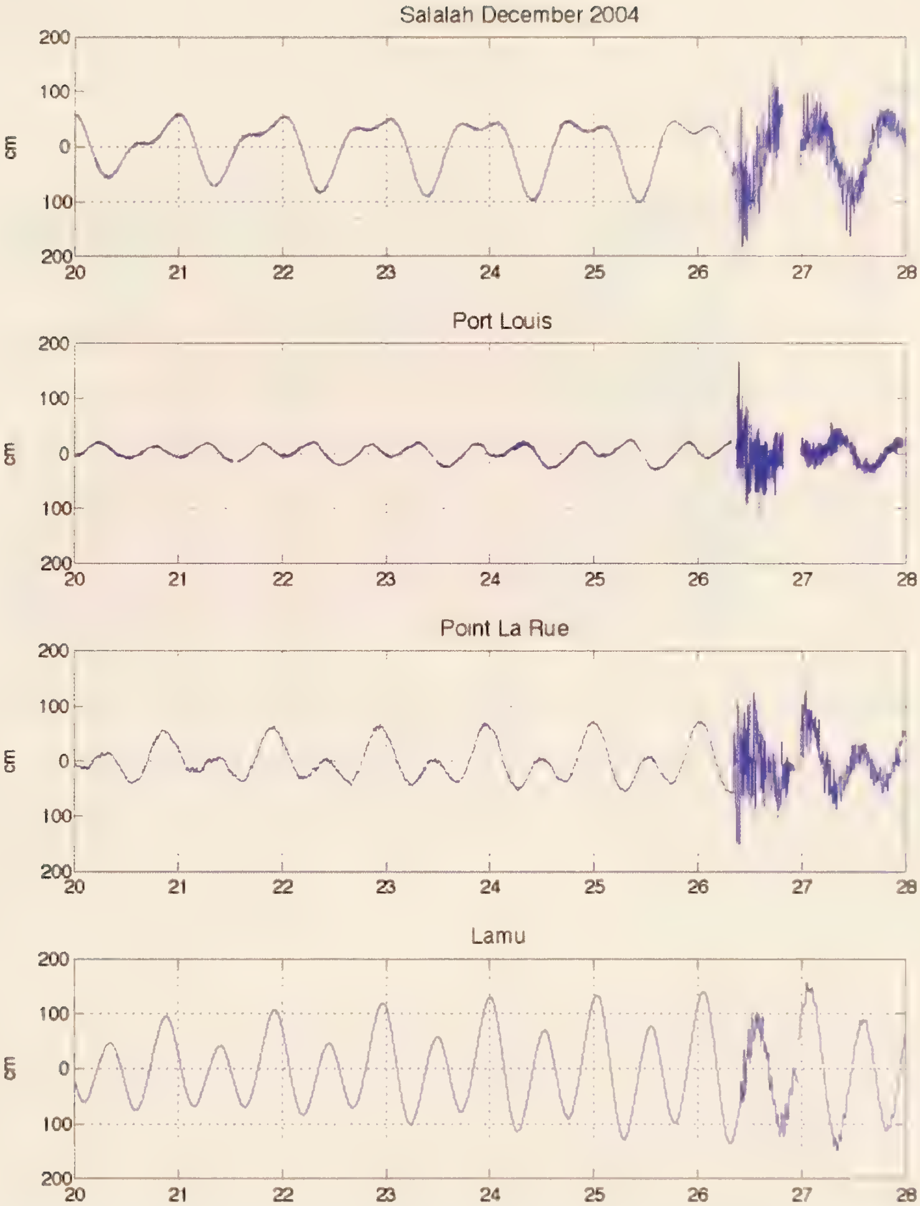

Figure 2. Water level records for Indian Ocean stations, showing the timing and magnitude of the 26 December, 2004 tsunami. Top-to-bottom: Salalah, Oman; Port Louis, Mauritius; Pointe La Rue, Seychelles; Lamu, Kenya. (Courtesy of J. Huthnance; available at http://www.pmel.noaa.gov/tsunami/indo20041226/tsunami2.pdf).

Tsunami amplitudes are greatest perpendicular to generating structures; thus the NNW–SSE orientation of the earthquake faultline between NW Sumatra and the Andaman Islands put the Seychelles Bank directly in line with the tsunami wave front as a simulation of wave heights 15 hours after the earthquake makes clear (Fig. 3; Yalciner et al., 2005).

Figure 3. Computer modelling of the 26 December, 2004 tsunami after 900 minutes (courtesy of A. Yalciner, U. Kuran, T. Taymaz) (available at: http://yalciner.ce.metu.edu.tr/sumatra/max-elev-sim-1.jpg).

Wave approach was, however, complicated by the large-scale refraction of the wave around southeastern Sri Lanka and southern India and by smaller-scale refraction effects across the Maldives chain and the Chagos Archipelago (NOAA 2005b) which were crossed by the tsunami ca. 4 hours and 2.5 hours earlier (Fig. 4; Merrifield et al., 2005).

All locations in the Indian Ocean to the west of the earthquake epicenter first experienced a wave crest (Merrifield et al., 2005). This first arrival was seen in the tide gauge at Pointe La Rue on Mahé at 08:08–08:12 Coordinated Universal Time (UTC) (12:08–12:12 local time) (Fig. 5). The level reached was 0.59 m above mean sea level datum (MSLD) (Fig. 6). The first arrival was on a rising tide, the predicted low tide having been at 07:26 UTC (11:26 local time); water levels were raised but only to typical high spring tide levels and not as high as the preceding high tide (which had peaked at 0.74 m MSLD). The first large wave arrived at 09:12 UTC (13:12 local time), registering a peak of 1.16 m MSLD. Both the first arrival and the first large wave were followed by significant drawdown events of –1.53 m MSLD at 08:56 and 09:36–09:40 respectively. However, these levels relate to the base of the tide-gauge stilling well and, therefore, most probably do not record the complete fall in water level. From eyewitness reports, Jackson et al. (2005) estimate that the true fall in water level may have been as low as –4.0 m below mean sea level. Thereafter a sequence of 8 waves was recorded by the tide-gauge in couplets of a larger wave of a magnitude similar to the first arrival followed by a smaller wave; superimposed on a rising tidal level the trend was for an increase in tsunami wave height peaking at 1.24 m at 12:52 UTC (16.52 local time) (Fig. 6). This wave was followed by a further noticeable drawdown event but after the next high wave, there was a lessening of activity after ca. 14:30 UTC (18:30 local time).

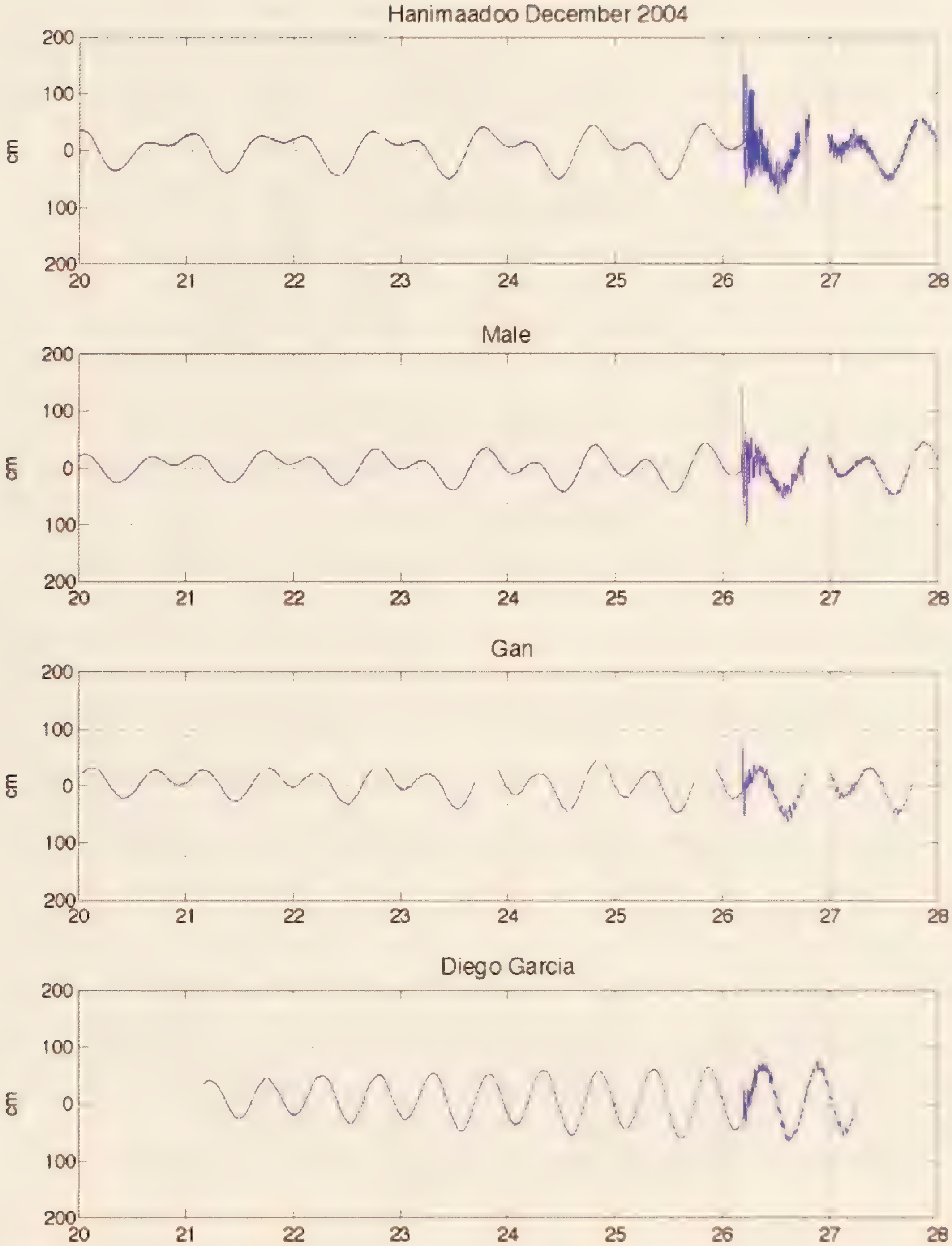

Figure 4. Water-level records for Indian Ocean stations, showing the timing and magnitude of the 26 December, 2004 tsunami. Top-to-bottom: Hanimaadoo, Maldives; Male, Maldives; Gan, Maldives; Diego Garcia, BIOT. (Courtesy of J. Huthnance; available at http://www.pmel.noaa.gov tsunami indo20041226 tsunami1.pdf).

However, activity continued into the next high-tide cycle. The predicted high-tide level (peak stage=75 cm) was considerably higher than the previous high-tide level (12 cm) and when the tsunami activity was superimposed on this high tide it resulted in a water level of 1.41 m at 00:56 UTC (04:56 local time) on 27 December, almost exactly 24 hours after the earthquake and 17 hours after the first arrival in the Seychelles (Figs. 5and 6).

Eyewitness accounts of tsunami impact on the east coast of Mahé broadly correspond to the timings extracted from the tide-gauge record. However, there are observations of significant drawdown events at 07:45–08:00 and 08:00 UTC (11:45–12:00 and 12:00 local time) at Anse Royale/Anse Forbans and Pointe aux Sel respectively which appear to lead the tide-gauge record (situated 14 km to the north of Anse Forbans and 7 km north of Pointe aux Sel) by almost one hour. However, the timings of the first large wave are broadly comparable to the tide-gauge record at these sites. At Anse a la Mouche, on the southwest coast, drawdown again appears to have occurred prior to that recorded in the tide-gauge record. The first large wave, however, appears to have been a later impact than on the east coast, timed at 09:25 UTC (13:25 local time), presumably reflecting the slowing of the tsunami wave front on refraction around the island. Victoria, Anse Royale and Anse Forbans on the east coast all experienced a second phase of flooding between 12:30 and 13:00 UTC (16:30–17:00 local time), as did Anse a la Mouche on the west coast half an hour later, a pattern consistent with the later arrival of the first large wave earlier in the day. In Victoria, it is clear that there was significant further flooding during the night of 26–27 December clearly associated with the wave peak timed at 01:00 UTC (05:00 local time) (Jackson et al., 2005). The tsunami struck Praslin, 40 km to the northeast of Mahé, in two separate surges, the first beginning at 08:10 UTC (12:10 local time). This was one hour before the first large wave was registered by the Mahé tide-gauge. There was a major drawdown event between this wave and the second larger wave which occurred at 08:24 (12:24 local time). Some locations registered large waves at ca. 09:30 and 10:00–11:00 UTC (13:30 and 14.30–15:00 local time) and the late afternoon wave of 26 December was seen at the northwestern end of the island at 12:45 UTC (16:45 local time) (Jackson et al., 2005).

The Pointe La Rue tide-gauge showed that activity continued throughout 27 December (Fig. 5), with an envelope of residuals around predicted tidal levels declining over a 24-hour period (Fig. 7). On 28 December residuals were still present but of the order of 10 cm or less; by 30 December the event was over (Fig. 7).

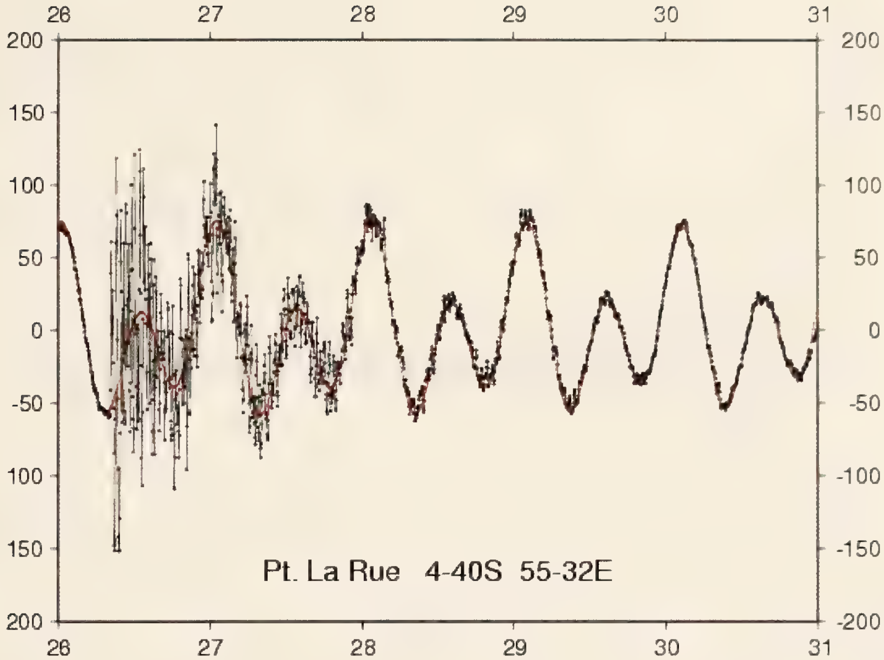

Figure 5. Predicted tidal-curve and water-level records, Pointe La Rue tide-gauge, Mahé, Seychelles, 26–30 December 2004. Heights in cm relative to Mean Sea Level Datum. (National Meteorological Service Seychelles / University of Hawaii Sea Level Center; available at: http://ilikai.soest.hawaii.edu/uhslc/iotd/plar1.html)

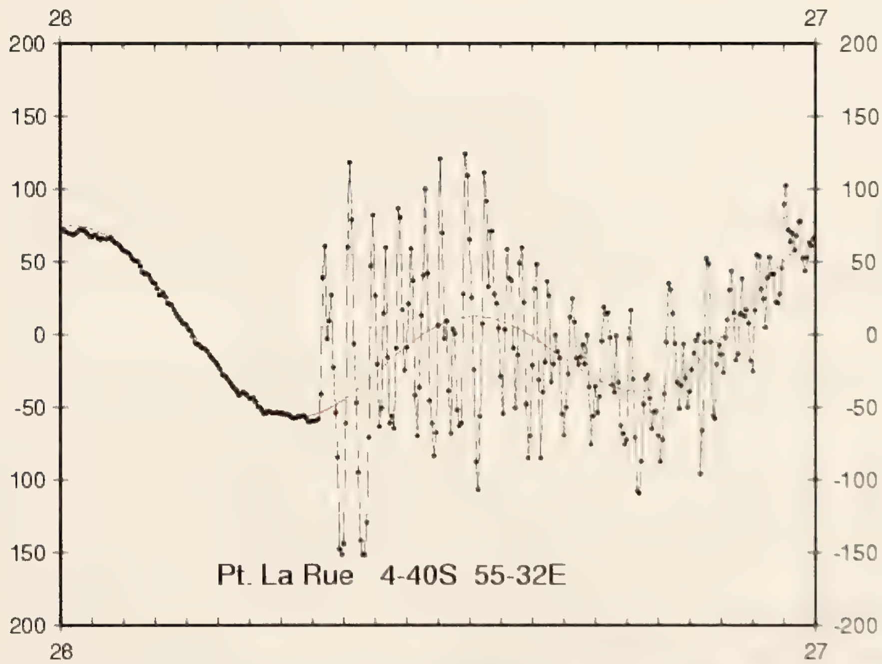

Figure 6. Detail of Figure 5 showing predicted tidal level and individual tsunami peaks and water-level drawdowns, 26 December, 2004. (National Meteorological Service Seychelles / University of Hawaii Sea Level Center; available at: http://ilikai.soest.hawaii.edu/uhslc/iotd/plar5.gif).

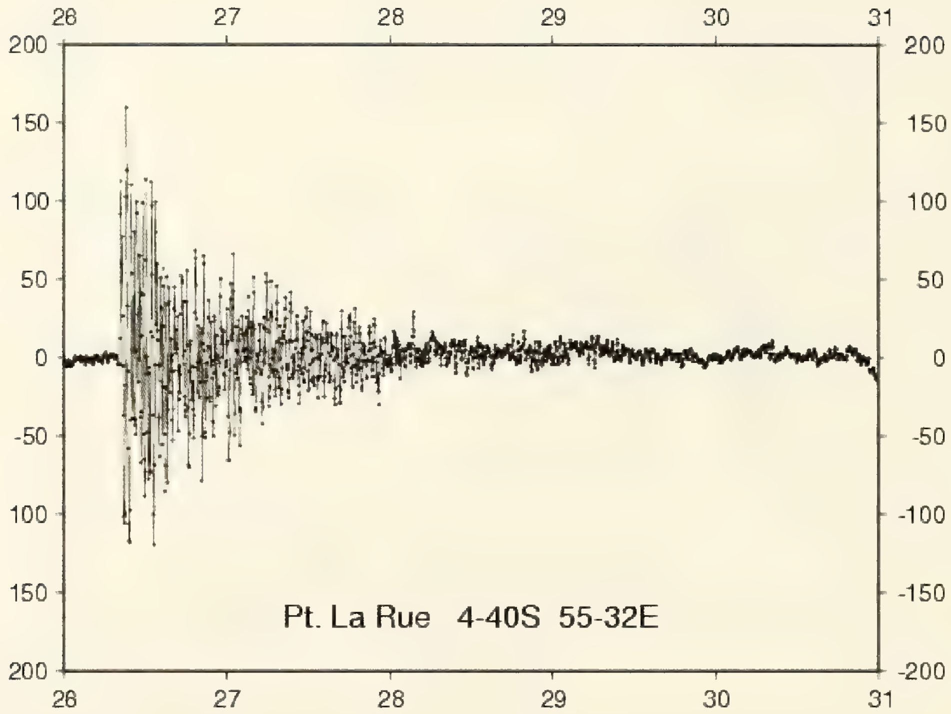

Figure 7. Water level residuals, Pointe La Rue tide-gauge, Mahé, Seychelles, 26–30 December, 2004. (National Meteorological Service Seychelles / University of Hawaii Sea Level Center; available at: http://ilikai.soest.hawaii.edu/uhslc/iotd/plarbr.html).

One of the striking features of the tsunami at an Indian Ocean basin scale was the differentiation between stations, associated with shelf areas, which showed a sustained tide-gauge signal over several days and those stations, predominantly in mid-ocean locations, which exhibited a strong initial signal but little subsequent "ringing" (Merrifield et al., 2005). The Seychelles clearly belonged to the first category. The implication is that the tsunami excited some form of seiche on the Seychelles Bank that both amplified and prolonged the tsunami signal; disentangling the two effects remains a major analytical challenge.

Spatial Characteristics: Granitic Islands of the Northern Seychelles

Statistics on tsunami wave heights at the shoreline, tsunami run-up (the tsunami's height above mean sea level at its limit of penetration inland) and inundation distance are reported in Table 1. They show the considerable site-to-site variability over distances often of less than 10 km. Thus, for example, Anse Boileau on the west coast of Mahé recorded a run-up of 2.5 m whereas Grande Anse 5 km to the north experienced inundation to 4.3 m. While impacts in general were greatest on eastern shores facing the direction of wave arrival, the significant tsunami signals present on the leeward coasts of Mahé and Praslin are noteworthy and suggest the operation of a series of controls at a number of different spatial scales.

At the largest scale, ocean-basin scale modelling of the December event (e.g., NOAA, 2005b) shows divergence of the tsunami around the shallow shelf areas of the Mascarene Plateau, the streaming of the wave-front around bank margins and the convergence of the wave in the lee of the Plateau at several locations, including on the Seychelles Bank (NOAA, 2005b). Refraction at the Bank scale is supported by the observation from the northwest point of Praslin that the wave came from the northeast (Jackson et al., 2005). It can be imagined that on the Seychelles Bank there were further refraction effects around the larger individual islands. Thus, for example, eyewitness accounts of tsunami wave arrival at Anse a la Mouche on the leeward southwest coast of Mahé reported that wave trains approached the bay from both the north and south (Jackson et al., 2005). Similarly, maximum wave heights on Praslin were experienced on the lee shore (Table 1).

Table 1. Maximum water levels at the coast and wave run-up, relative to mean sea level, of the 26 December, 2004 tsunami in the Seychelles (from Jackson *et al.*, 2005).

Location		**Maximum Water Level Near Shoreline (m)**	**Wave Run-up (m)**	**Inundation Distance (m)**
North East Point	Mahé	2.2		100
Victoria	Mahé	>1.7	>1.4	>200
Seychelles International Airport	Mahé	3.0		200
Anse aux Pins	Mahé	>1.9		>50
Pointe au Sel	Mahé	2.8	2.3	>35
Anse Royale (N)	Mahé	>3.8	3	>100
Anse Royale (S)	Mahé	>4.4		>45
Anse Forbans	Mahé	2.8		20
Baie Lazare	Mahé	1.6		20
Anse a la Mouche	Mahé	3.0 (3.5)*	2.5	250
Anse Boileau	Mahé	2.5		53
Grand Anse	Mahé	4.3		nil
Beau Vallon	Mahé	1.7		10
Chevalier Bay	Praslin	3.1		140
Anse Possession	Praslin	3.0		35
Anse Petit Cour	Praslin	2.5		225
Anse Volbert (1)	Praslin	1.9		100
Anse Volbert (2)	Praslin	2.0		>100
Grande Anse	Praslin	3.6		>50
Baie Ste Anne	Praslin	1.8		nil

*Figure of 3.5 m at Anse a la Mouche records height of wave surge damage.

Within these island-wide patterns of incidence, tsunami impacts were sensitive to changes in shoreline orientation. Thus, for example, at Beau Vallon, Mahé, which faces north, the maximum run-up level was only 1.7 m, slightly above a normal high-tide. Similarly, the southeast-facing Baie Ste Anne on Praslin only suffered inundation to typical high-tide level (Jackson et al., 2005). In addition, waves were funnelled between rocky headlands into embayments and influenced by offshore fringing reef topography, particularly the presence or absence of deep-water passages through the reef system. In reef-fronted locations it appears that the tsunami waves broke on the reef and then propagated across the reef as a bore. These water flows were influenced by wave interactions (including wave refraction and reflection) and interactions with bottom topography. In particular, it appears that tsunami run-up was often greatest at the head of deep channels through fringing reefs. Finally, at the very local level it is clear that tourist development very close to, or even on, the beach made many buildings highly vulnerable to water levels even only slightly above normal high-tide levels and to surge velocities of 3.3–4.4 m s^{-1}, particularly where the natural energy dissipation afforded by the presence of upper beach berms and/or coastal vegetation had been removed to enhance beach access (Jackson et al., 2005).

Impacts on the Marine Environment: Granitic Islands of the Northern Seychelles

A series of rapid assessments of marine environments in the granitic islands between 30 December, 2004 and 13 February, 2005 (Obura and Abdulla, 2005) identified two major patterns of coral-reef damage related to location and substrate type. The most heavily impacted areas were carbonate reef substrates in the northern islands around Praslin (including Curieuse, La Digue, Felicite, Isle Coco and Ste. Pierre). Here levels of substrate damage (movement of rubble, erosion gullies within rubble deposits) exceeded 50%, and levels of direct coral damage (coral toppling and overturning) exceeded 25%. By comparison, around Mahé damage levels on carbonate substrates were less than 10%. Throughout the granitic islands of the Seychelles, levels of damage on granitic substrates were less than 1% (Obura and Abdulla, 2005). Cemented reef substrates showed little evidence of coral breakage or overturning; where damage was present it was restricted to water depths of less than 50 cm. However, many reef surfaces in the granitic Seychelles are currently characterized by poorly consolidated surfaces resulting from reef-framework degradation, following the coral-bleaching and mass-mortality event associated with the Indian Ocean warming of 1998 (e.g., Spencer et al., 2000). There was considerable movement of reef rubble in such settings under tsunami surge conditions, and the dislocation and damage of live coral colonies established on such surfaces (Obura and Abdulla, 2005).

It is important to realise that a substantial sector of the east coast reefs has been profoundly modified since the classical descriptions of them by Lewis (1968,1969), Taylor (1968) and the summaries by Braithwaite (1984) and Stoddart (1984). Starting with the construction of the airstrip in 1971, large-scale reclamation now extends for 11 km from north of Victoria to Pointe La Rue. The reclamation, used for housing, light

industry, and rapid road access to the airport, typically is separated from the old island shoreline by open water. Surges in sea-level can thus be ponded behind them and can only drain back to sea via egress channels. This accounts for the destruction of the bridge shown in Plate 3. Drawdown and upsurge were also severely damped in the lee of the reclamations.

The tsunami resulted in beach cliffing of 2.5 m at Anse Kerlan, northwest Praslin and a calculated loss of 200 x10^3 m^3 of beach sand offshore (UNEP, 2005). The waves also mobilized marine sediments, both stripping sediments from coral-reef rubble beds and depositing sediments in new locations; back-drainage from run-up may have also deposited terrestrial sediments on fringing reefs. These processes were exacerbated by stormy weather in the days immediately following the tsunami which generated rough seas. Rainfall totals in excess of 250 mm triggered landslides on Mahé and led to high terrestrial runoff but it is not clear if fluvial sediments reached reef environments. Fringing reefs were exposed by the significant drawdown events (e.g., reported for Anse Royale, Anse Forbans and Anse a la Mouche, Mahé; exposure of massive corals at Anse Petit Cour, Praslin at 08:00 UTC, 26 December; Jackson et al., 2005) but it is unlikely that these events were of sufficient duration to cause coral death. Seagrasses at Baie Ternai, Mahe were smothered by carbonate sediments but general damage levels in seagrass beds were low. The causeway enclosing the mangrove parkland at Curieuse was toppled inwards by tsunami waves but no damage to the mangroves was noted (Obura and Abdulla, 2005).

Tsunami Impacts in the Southern Seychelles

A collaborative expedition between the Khaled bin Sultan Living Oceans Foundation, Cambridge Coastal Research Unit and SCMRT-MPA to the southern Seychelles was conducted onboard M.Y. Golden Shadow, 10–28 January 2005. Although the primary focus of this expedition was airborne mapping of the outer islands, due to the timely nature of this expedition, it was expected that impacts of the tsunami on the remote southern islands of the Seychelles could also be reported. The expedition visited the islands of Providence, St. Pierre, Alphonse and St. François and the southern islands of the Amirantes group (D'Arros, Desroches, Desnoeufs, Marie-Louise, Boudeuse, Etoile and Poivre) some previously described by Stoddart (1970). Stoddart also visited Aldabra and Assumption in April 2005.

On all the southern Seychelles islands visited no physical damage to either the terrestrial or marine environments was observed. The littoral hedge was intact in all cases and there was no evidence of beach sediment movement or water inundation in the littoral area. Underwater there was no evidence of reef damage; thus, for example, there was no physical damage to the branching corals (principally *Pocillopora* spp.) that dominate these reefs and no coral toppling. The islands of Providence, Alphonse, D'Arros, Desroches, Marie-Louise and Poivre are inhabited. In all cases, island personnel said that there had not been any impact caused by the tsunami and they hardly noticed the event. On Providence Island, the island manager was radioed from Mahé and warned of the tsunami waves approaching. The I.D.C. (Island Development Company) manager

on Assumption and the manager of the S.I.F. (Seychelles Island Foundation) Research Station on Aldabra both state that in spite of radio warnings they did not detect any tsunami surges. It is fair to add that if there had been a substantial surge it would have impacted rocky coastlines in the east of each island, and that in both cases the settlements are in protected western locations. Providence Island is at the northern tip of the large (approximately 400 km^2) Providence Bank, and here the tsunami was observed as a sudden influx of water approximately 10 cm higher than normal that remained for a few minutes before dropping to a normal level. No accurate time could be given for this observation, but it was said to be "about lunch-time". Unfortunately there are no reports of tsunami effects on Coetivy.

Computer modelling of the passage of the tsunami wave front indicates a regional scale refraction of the wave front towards the southwestern Indian Ocean (NOAA, 2005b). This would have led to an increase in the length of wave crest and hence lower wave heights to the south. In addition, there are considerable contrasts in bathymetric setting between the two areas. In contrast to the northern, granitic islands of the Seychelles, the southern islands are typically low-lying sand cays (islands of the Amirantes) and atolls (Alphonse, St. François; Desroches is a drowned atoll) with the exception of St. Pierre which is a raised platform reef island. The granitic islands protrude from the shallow Seychelles Bank (mean water-depth 44-65 m; Braithwaite, 1984), but the southern islands are situated in open ocean and exhibit steeply shelving fore-reef slopes or vertical reef wall drop-offs, surrounded by deep water (>5,000 m). Thus when the tsunami approached the region of the southern islands, the waves passed through the gaps between the islands and there was no increase in wave amplitude due to the continuity of deep water and lack of a shallow barrier in the flow path. This would explain the contrast between the lack of tsunami impacts observed on the southern Seychelles islands compared to the significant impacts observed on the granitic islands of the Seychelles Bank.

ACKNOWLEDGEMENTS

Observations in the Republic of Seychelles were supported through a collaborative expedition between the Khaled bin Sultan Living Oceans Foundation, Cambridge Coastal Research Unit, University of Cambridge and Seychelles Centre for Marine Research and Technology – Marine Parks Authority (SCMRT–MPA). Fieldwork in the southern Seychelles was conducted onboard the Khaled bin Sultan Living Oceans Foundation vessel, the M.Y. Golden Shadow, 10–28 January 2005. We are grateful to Capt. P. Renaud, Executive Director, Khaled bin Sultan Living Oceans Foundation for extensive logistical support and to the Seychelles Island Development Company for permission to visit islands in the Southern Seychelles.

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Plate 1

Plate 2

Plate 1. Internal fissuring and collapse of dock quay, Port Victoria, Mahé.

Plate 2. Failure of quayside, Port Victoria, Mahé.

Plate 3. Road bridge washout from seaward drainage of tsunami waters from coastal lagoon, west coast of Mahé.

Plate 4. Road bridge washout following drainage of tsunami waters, southwest Mahé.

ATOLL RESEARCH BULLETIN

NO. 544

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NATIONAL MUSEUM OF NATURAL HISTORY
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WASHINGTON, D.C., U.S.A.
JULY 2007